Problem Assessment for the Columbia/Snake River Temperature TMDL

Preliminary Draft

November 4, 2002

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Introduction

Under Section 303(d) of the Clean Water Act, states must identify waters for which effluent limitations, as required by Section 301, are not sufficient to implement established water quality standards. EPA, Oregon and Washington have identified portions of the main stem of the Columbia River from the International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon, and the Snake River from its confluence with the Salmon River at river mile 188 to its confluence with the Columbia River as water quality limited for temperature pursuant to Section 303(d) of the Clean Water Act. Section 303(d) also requires the development of a Total Maximum Daily Load (TMDL) for water bodies included on the 303(d) list. The scope of this Problem Assessment is water temperature in the main stem segments of the Columbia River from the Canadian Border to the Pacific Ocean and the Snake River from its confluence with the Salmon River to its confluence with the Columbia River. This information will be utilized as the framework for the subsequent TMDL.

This Problem Assessment briefly describes the Columbia Basin: geography, climate, hydrology, human development, salmon stocks and Indian Tribes. This is followed by an evaluation of water temperature problems in the Columbia and Snake Rivers, utilizing existing data and the results of temperature modeling. Finally, the effects of elevated temperatures on salmon and white sturgeon are evaluated.

Temperature Assessment

The water quality standards applicable to most of the river system under consideration in this TMDL restrict temperature increases over specified temperature criteria due to human activities. For example, the Washington standard for the lower Columbia River is:

> *"Temperature shall not exceed 20 C due to human activities. When natural conditions exceed 20 C no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 C..."*

Evaluation of existing water temperature against this standard requires knowledge or estimates of natural water temperature or water temperature in the absence of human activity. This temperature assessment relies on existing temperature data and mathematical modeling of the temperature to describe the existing temperature regime of the impounded river and the natural temperature regime of the un-impounded or free flowing river in the absence of human activity.

Both the temperature observations and the temperature simulations provide estimates of water temperature. Since there are information gaps and uncertainties associated with both the observations and the simulations both are used to gain an understanding of the free flowing and impounded temperature regimes and the relative importance of dams, point sources and tributaries in altering the natural regime of the rivers.

There is a considerable record of temperature data from the Columbia and Snake Rivers. McKenzie and Laenen (1998) assembled temperature data from 84 stations along the two rivers within the study area of this TMDL. However, the extensive data base from along the rivers must be used with caution. Little, if any of the data were collected with the express objective of evaluating temperature in the river. Few of the sampling sites have quality assurance objectives or followed quality control plans. Temperature measured at the same time at one dam can vary quite a bit depending on whether it was measured in the fore bay, the tail race or the scroll case. In using these data it is important to compare like stations along the river (e.g. scroll case to scroll case, fore bay to fore bay) and to use long records or repetitive examples when drawing general conclusions about temperature trends.

The temperature model was developed to augment the understanding of temperature in the river derived from analysis of the data record. There is a good deal of information available for development of the temperature model. For example there are 30 years of continuous weather, flow and water temperature data. However, there are also modeling challenges that cause uncertainty in the modeling results. For example there is little information on temperature in the free flowing river to compare with simulated temperatures. Therefore, the problem assessment relies heavily on both data analysis and modeling analysis.

The analysis in the Problem Assessment provides the following information about the natural and existing temperature regimes of the river:

- The temperatures of the Columbia and Snake rivers frequently exceed state and tribal water quality criteria for temperature during the summer months throughout the area covered by this TMDL.

- The water temperatures of the rivers before construction of the dams could get quite warm, at times exceeding the 20 ^oC temperature criteria of Oregon and Washington on the lower Columbia River.

- However, these warm temperatures were less frequent without the dams in place. Temperature observations show that the frequency of exceedance at Bonneville Dam of 20 ^oC increased from about 3% when Bonneville was the only dam on the lower river to 13% with all the dams in place.

- The dams appear to be a major cause of warming of the temperature regimes of the rivers. Model simulations using the existing temperatures of tributaries and holding tributary temperatures to 16 ^oC revealed that only the Salmon and Clearwater rivers affect average water temperature in the Snake and only the Snake affects water temperature in the Columbia.

- Climate change plays a role in warming the temperature regime of the Columbia River. The Fraser River, with no dams, shows an increasing trend in average summer time temperature of 0.012 ^oC/year between 1941and 1998, and 0.022 ^oC/year between 1953 and 1998. If applied to the Columbia, this would account for 26% to 48% of the temperature increase seen at Bonneville dam since 1939.

- The modeling strategy used here illustrates the effect dams have on water temperature independent of climate change. The warming effect of dams occurs in addition to the effects of climate.

- The average water temperatures of the free flowing river exhibits greater diurnal fluctuations than the impounded river.

- The free flowing river average water temperature fluctuates in response to meteorology more than the impounded river. Cooling weather patterns tend to cool the free flowing river but have little effect on the average temperature of the impounded river.

- The free flowing river water temperatures cool more quickly in the late summer and fall.

- Alluvial flood plains scattered along the rivers moderated water temperatures, at least locally, and provided cool water refugia along the length of the rivers.

- The existing river can experience temperature gradients in the reservoirs in which the shallow waters are warmer.

- Fish ladders, which provide the only route of passage for adult salmon around the dams, can be warmer than the water in the tail race of the dams.

Effects on Salmonids and White Sturgeon

Two levels of concern, “initial” and “serious” are discussed for the effects of increased water temperature on chinook, sockeye, and coho salmon, steelhead and bull trout, and white sturgeon in the Columbia Basin. The level of initial concern is the lowest level that may cause the adverse effect. The level of serious concern is when a fish population is exposed to conditions that will very likely cause the adverse effects. These levels of concern may not apply to these same species of fish occurring outside the Columbia Basin, especially in the southern parts of their range.

From an overall review of the levels of initial concern, with some exceptions, it appears that most of the adverse effects will begin to occur as water temperatures increase to 13 - 15 EC. The exceptions at lower temperatures are the requirements for steelhead smoltification (<12 EC) and for low temperature levels (<12 EC) required by adult bull trout. The exceptions at higher temperatures (16 - 18 EC) are reduced salmonid growth, reduced chinook distribution, increased predation, and impaired bull trout holding and migration.

In a similar review of the levels of serious concern, there is some overlap because of the low temperatures required for smoltification of chinook, sockeye, and steelhead. The remainder of the temperatures fall in the 18 - 22 EC range. It should also be noted that as water temperatures increase into the 20+ EC range chronic and acute toxicity become a concern, particularly if the fish are sustaining multiple stressors, like passing through dams.

The time period of concern for bull trout would vary with location in the Columbia and Snake rivers within the study area, but would generally be during the late summer and early fall when adult fish are moving out of main channel areas into tributaries. The time period of concern for fall chinook salmon spawning is from mid-October to the third week of November in the Columbia River and from mid-October to mid-December in the Snake River. Growth is an issue all year for yearling salmonids, and for subyearlings it is an issue from early March to mid-late September. The time periods of concern for outmigrating juvenile salmonids extend from early April to mid-late September, depending of the species. Returning adult salmonids are likely in the river all year long, but begin arriving in numbers at Bonneville Dam in early March and continue up the Columbia River until about mid-November and up the Snake River until early-mid December.

The period of concern for white sturgeon spawning and incubation is from April through August each year. Depending on the location in the river, white sturgeon may spawn from the end of April through July (Parsley et al. 1993, McCabe & Tracy 1994). The spawning period is followed by a 3-week incubation period (Wang et al. 1985).

1.0 INTRODUCTION AND SCOPE OF THE PROBLEM ASSESSMENT

The objective of the Clean Water Act (as amended by the Water Quality Act of 1987, Public Law 100-4) is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. Each state has developed standards for water quality that are used to judge how well the objectives of the Clean Water Act are being achieved. The water quality standards consist of the designated beneficial uses of the water and the water quality criteria necessary for achieving and maintaining the beneficial uses.

Under Section 303(d) of the Clean Water Act, states must identify waters for which effluent limitations, as required by Section 301, are not sufficient to implement established water quality standards. EPA, Oregon and Washington have identified portions of the main stem of the Columbia River from the International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon, and the Snake River from its confluence with the Salmon River at river mile 188 to its confluence with the Columbia River as water quality limited for temperature pursuant to Section 303(d) of the Clean Water Act. This designation arises from an analysis of data (Smith, 2001; Washington DOE, 1998; Oregon DEQ, 1998) showing these waters do not meet water quality standards during all or part of the year. Table 1-1 lists the reaches of the Columbia and Snake Rivers in the study area that have been included by EPA and the States on the 303(d) list for temperature and require a TMDL for temperature.

Table 1-1. Segments of the Columbia and Snake rivers listed for temperature in the study area

State	Water Body Name	River Mile	Parameter	Action Needed
ID*	Snake River	139.1 -188.0	Temperature	TMDL
OR	Snake River	176.1-188.0	Temperature	TMDL
OR	Columbia River	0.0 – 309.3	Temperature	TMDL
WA	Columbia River	19 sites	Temperature	TMDL
WA	Snake River	8 sites	Temperature	TMDL

*Listed by EPA 2001

These same reaches of the Columbia and Snake Rivers, depicted in Figure 1-1, encompass most of the action area addressed by the Federal Columbia River Power System (FCRPS) Biological Opinion for Salmon under the Endangered Species Act (ESA) (NMFS, 2000). That Biological Opinion addresses the effects of the FCRPS on 12 salmonid species listed pursuant to the ESA as threatened or endangered. It also addresses the effects of degraded habitat on the 12 listed species and identifies water temperature as an important factor that "affects salmonid metabolism, growth rate and disease resistance, as well as the timing of adult migrations, fry emergence, and smoltification." (NMFS, 2000).

The Biological Opinion states that the effect of water quality [water temperature and total dissolved gas (TDG)] on Federally listed anadromous fish in the basin requires that water quality and ESA listings be addressed in a coordinated manner. "Therefore, the Environmental Protection Agency (EPA), the National Marine Fisheries Service (NMFS), the U.S. Fish and Wildlife Service (USFWS), and the Federal Action Agencies (U.S. Army Corps of Engineers [Corps]; Bureau of Reclamation [BOR]; and Bonneville Power Administration [BPA]) are undertaking efforts to conserve listed species under the ESA and create a nexus of water quality improvements consistent with the CWA" (NMFS, 2000). Appendix B of the Biological Opinion charts a course for development of a water quality plan for the main stem Columbia and Snake Rivers to address CWA objectives. This water quality plan is to be "consistent with the Columbia River and Snake River main stem total maximum daily load (TMDL) limits that are currently being developed by EPA, the states, and the Tribes." (NMFS, 2000)

The scope of this Problem Assessment and the TMDL to follow is water temperature in the main stem segments of the Columbia River from the Canadian Border to the Pacific Ocean and the Snake River from its confluence with the Salmon River to its confluence with the Columbia River. This TMDL, along with TMDLs that the states are developing for TDG on the main stems, will serve as the nexus between CWA and ESA, addressing the importance that both Acts place on maintaining ecosystem integrity. Chapter 2 of the Problem Assessment briefly describes the Columbia Basin. It discusses the factors that likely affect water temperature: geography, climate, hydrology, and development. It then briefly summarizes the status of the beneficial use of the rivers that is greatly effected by elevated temperatures, salmon. Further, it very briefly discusses the Indian Tribes of the Columbia Basin that rely on salmon resources and for whom federal agencies have treaty and trust responsibilities. Chapter 3 of the Problem Assessment discusses the status of water temperature in the Columbia and Snake Rivers, describing processes important to water temperature, the Water Quality Standards that apply to the main stems, existing temperature data and the results of temperature modeling. Chapter 4 evaluates the effects of elevated temperatures on salmon resources.

2.0 GENERAL DESCRIPTION OF THE COLUMBIA BASIN

2.1 Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the states of Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming. The Columbia rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, British Columbia. It enters the United States from the Okanagan Highland Province, a mountainous area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin—a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt—and flows south across the state of Washington. Near Pasco, Washington, and the confluence with the Snake River, the Columbia turns west, forms the border between Oregon and Washington, and flows more than 300 miles through the Cascade Mountain Range to the Pacific Ocean near Astoria, Oregon.

The headwaters of the Snake River are upstream of Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7,000 feet above sea level. The river flows west across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western edge of Idaho, it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. The major tributaries of the Snake in Idaho within this project area are the Clearwater River and the Salmon River.

The Snake River is the Columbia's largest tributary. Other major tributaries in the project area include the Spokane, Yakima, Deschutes, and Willamette Rivers. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in

Lake Franklin D. Roosevelt (Lake FDR). The Yakima River begins in the Cascade Mountains and flows east and south to join the Columbia near the Tri-Cities. Both the Deschutes and Willamette rivers have their headwaters in Oregon; the Deschutes rises in central Oregon and flows north across lava flows of the Columbia Basalt, while the Willamette begins in the Cascade Mountains and flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

2.2 Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely, depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while annual precipitation can exceed 100 inches per year in some of the mountainous regions of Canada.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100 EF (37.8 EC) for extended periods. Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavy snow falls in the mountains. The snow pack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snow pack is incorporated into the extensive system of glaciers in the basin; however, between the months of March and June, depending on elevation, much of the snow pack begins to melt. The resulting hydrograph is typical of a snow melt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing, and summer air temperatures are seldom above 100 ºF (37.8 ºC) for long periods. Average annual precipitation west of the Cascades is more than 40 inches in most areas. Precipitation recorded at coastal stations is typically higher. Below about 5,000 feet, most of the precipitation falls as rain, with 70 percent or more falling between October and March.

2.3 Hydrology

The hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control, and transportation projects. However, the hydro graph still has the characteristics of a snow melt regime. Stream flows are low during the winter, and increase beginning in spring and early summer as the snow pack melts. Melting of the winter snow pack generally takes place in May and June, and stream flows increase until the snow pack can no longer support high flows. Flows then recede gradually during the summer and are derived from reservoir storage and from ground water recession into the fall and winter. Occasionally, runoff from winter storms augments the base flow and can increase river discharge rapidly.

Mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table 2-1.

Table 2-1. Mean annual discharges at selected sites on the main stem Columbia and Snake rivers

Station Name	Gage #	Station Location		Period of Record	Average Flow (cfs)
		Latitude	Longitude		
Snake River near Anatone, Washington	13334300	46º 05'50"	116º 58'36"	1958-1995	34800
Tucannon near Starbuck, Washington	13344500	46º30'20"	118º 03'55	1914-1996	176
Palouse River near Hooper, Washington	13351000	46º15'02"	118º 52'55	1898-1996	588
Snake River below Ice Harbor Dam	13353000	46º15'02"	118º 52'55"	1913-1992	53400
Columbia River at the International Boundary	12399500	49º 00'03"	117º 37'42"	1938-1996	99200
Columbia River at Grand Coulee	12436500	47º 57'56"	118º 58'54"	1923-1996	108200
Columbia River at Bridgeport, Washington	12438000	48º 00'24"	119º 39'51"	1952-1993	110200
Okanogan River at Malott, Washington	12447200	48º 16' 53"	119º 42' 12"	1965-1996	3050
Methow River near Pateros, Washington	12449950	48º 04' 39"	119º 59' 02"	1959-1996	1560
Columbia River below Wells Dam	12450700	47º 56'48"	119º 51'56"	1968-1996	109400
Columbia River at Rocky Reach Dam	12453700	47º 31' 28"	120º 18'04"	1961-1996	113200
Wenatchee River at Monitor, Washington	12462500	47º 29' 58"	120º 25' 24"	1962-1996	3250
Columbia River below Rock Island Dam	12462600	47º 19'57"	120º 04'48"	1961-1996	116300
Crab Creek near Moses Lake, Washington	12467000	47º 11' 22"	119º 15' 53"	1942-1996	63
Columbia River below Priest Rapids Dam	12472800	46º 37'44"	119º 51'49"	1918-1996	118400
Walla Walla River at Touchet, Washington	14018500	46º 01' 40"	118º 43' 43"	1951-1996	568
John Day River at McDonald Ferry, Oregon	14048000	45º 35' 16"	120º 24' 30"	1904-1996	2080
Deschutes River at Moody, near Biggs, Oregon	14103000	45º 37' 20"	120º 54' 54"	1907-1996	5800
Columbia River at the Dalles	14105700	45º 36'27"	121º 10'20"	1878-1996	191000

2.4 Salmon Resources

According to the Independent Scientific Group (1996), 200 distinct anadromous salmon stocks returned several million adult salmon and steelhead to the Columbia River prior to development of the basin. All five native eastern Pacific salmon species historically returned to the Columbia River, but today (with some exceptions) most chum, pink and wild coho stocks are extinct and the other species are at risk of extinction. In fact, 69 of the 200 stocks have been identified as extinct and 75 others are at risk of extinction in various parts of the basin (ISG, 1996) Historical estimates of average salmon runs in the portion of the Columbia Basin upstream of Bonneville Dam exceeded 5 to 11 million fish, but, as of 1995, average returns above Bonneville Dam were fewer than 500,000 fish and 80% of those were from hatcheries (CRITFC, 1995).The Independent Scientific Group concluded that the “development of the Columbia River for hydropower, irrigation, navigation and other purposes has led to a reduction in both the quantity and quality of salmon habitat, and most critical, a disruption in the continuum of that habitat” (ISC, 1996).

Table 2-2 lists the 12 stocks (or species under the ESA) listed by NMFS under the ESA and present within the TMDL project area.

Table 2-2 : The 12 species of Columbia Basin salmonids listed under the Endangered Species Act and located in waters within the TMDL project area.

Listed Species	Date Listed/Federal Register Notice	Date Critical Habitat Designated/ FR Notice
Snake River Spring/Summer Chinook (*Oncorhynchus tshawytscha*)	04/22/92 [58 FR 14653]	12/28/93 [64 FR 57399] 10/2593 [64 FR 57399]
Snake River Fall Chinook (*O. tshawytscha*)	04/22/92 [57 FR 14653]	12/28/93 [58 FR 68543]
Upper Columbia River Spring Chinook (*O. tshawytscha*)	03/24/99 [64 FR 14308]	02/16/00 [65 FR 7764]
Upper Willamette River Chinook (*O. tshawytscha*)	03/24/99 [64 FR 14308]	02/16/00 [65 FR 7764]
Lower Columbia River Chinook (*O. tshawytscha*)	03/24/99 [64 FR 14308]	02/16/00 [65 FR 7764]
Snake River Steelhead (*O. mykiss*)	08/18/97 [62 FR 43937]	02/16/00 [65 FR 7764]
Upper Columbia River Steelhead (*O. mykiss*)	08/18/97 [62 FR 43937]	02/16/00 [65 FR 7764]
Middle Columbia River Steelhead (*O. mykiss*)	03/25/99 [64 FR 14517]	02/16/00 [65 FR 7764]
Upper Willamette River Steelhead (*O. mykiss*)	03/25/99 [64 FR 14517]	02/16/00 [65 FR 7764]
Lower Columbia River Steelhead (*O. mykiss*)	03/19/98 [63 FR 13347]	02/16/00 [65 FR 7764]
Columbia River chum (*O. keta*)	03/25/99 [64 FR 14508]	02/16/00 [65 FR 7764]
Snake River sockeye (*O. nerka*)	11/20/91 [56 FR 58619]	12/28/93 [58 FR 68543]

2.5 Indian Tribes

Thirteen tribes, listed below, have management authority for fish, wildlife and water resources within their reservations, as well as other legal rights included in treaties and executive orders:

Confederated Tribes of the Colville Reservation;
Confederated Tribes of the Umatilla Indian Reservation;
Confederated Tribes of the Warm Springs Reservation;
Confederated Tribes and Bands of the Yakama Nation;
Nez Perce Tribe;
Spokane Tribe of Indians;
Couer d' Alene Tribe;
Kalispel Tribe of Indians;
Kootenai Tribe of Idaho;
Salish-Kootenai Tribes of the Flathead Indian Reservation;
Shoshone-Bannock Tribes of the Fort Hall Reservation;
Burns-Paiute Tribe;
Shoshone-Paiute Tribes of the Duck Valley Reservation.

Four of these tribes, Confederated Tribes of the Umatilla Indian Reservation, Confederated

Tribes of the Warm Springs Reservation, Confederated Tribes and Bands of the Yakama Nation, and Nez Perce Tribe reserved their rights to take anadromous fish in treaties with the United States in 1855. The tribes gave up control of large tracts of land but retained ownership of the salmon runs that are vital to their culture (CRITFC, 1995). The tribes reserved the right to take fish within their reservations, at all usual and accustomed fishing sites on lands ceded to the United States government and at all the usual and accustomed fishing sites outside the reservation or ceded areas, but these rights are meaningless if there are no fish to be taken (CRITFC, 1995).

Two Tribes, the Confederated Tribes of the Colville Reservation, and the Spokane Tribe of Indians have reservations that include portions of the Columbia River. Both tribes have developed water quality standards for the potions of the Columbia within their reservations. The Colville WQS have been promulgated by EPA and are national standards. The Spokane standards, at this point are reservation standards, but have been submitted to EPA for approval.

Salmon are intrinsic to the culture and identity of the Indian Tribes of the Columbia Basin. Salmon are part of their spiritual and cultural identity. Historically the tribes were wealthy people because of flourishing economies based on salmon. Salmon was the primary food source of the tribes and continues to be essential to their nutritional health. The tribes believe that without the salmon returning to their rivers and stream, they would cease to be Indian people (CRITFC, 1995).

2.6 Water Resources Development

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River in the United States above Bonneville Dam that remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the United States (Table 2-3), from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head available in this segment of the Columbia River main stem. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed, with 19 dams on the main stem, four of them in the TMDL project area.

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation, and hydroelectric power generation. There are approximately 7 million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington, and 1.3 million acres in Oregon (Bonneville Power Administration et al., 1994). The system has the capacity for generating more than 20,000 megawatts of hydroelectric energy, and slack-water navigation now extends more than 460 river miles from the mouth at Astoria, Oregon, to Lewiston, Idaho.

In the United States, federal agencies, private power companies, and public utility districts own the dams in the Columbia River Basin. The Columbia Treaty between the United States and Canada governs transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

Table 2-3. Hydroelectric projects on the main stem Columbia and Snake rivers included in the scope of the analysis

Project	River Mile	Start of Operation	Generating Capacity (megawatts)	Storage Capacity (1000s acre-feet)
Columbia River				
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2,069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Snake River				
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

2.7 Population/Land Use/Economy

The Columbia Basin includes sparsely populated rural areas and dense metropolitan areas. Much of the Columbia Basin is located east of the Cascade Mountains. This area is sparsely populated with a density of 11 people per square mile compared to a national average of 70 people per square mile (ICBEMP,2000). Based on the 1998 census, 3.3 million people live in the portion of the basin east of the Cascade Mountains. Nearly half of this population lives in 12 of the 100 counties east of the Cascades. Only six counties have sufficient population to be classified as metropolitan counties. Thirty one percent of the residents east of the Cascades live in urban areas compared to the national average of over 77% and over 90% of the 470 communities east of the Cascades are considered to be rural communities (ICBEMP, 2000). There are 2 cities east of the Cascades with populations over 100,000 people: Spokane, WA; and Boise, ID. (USCB, 2000).

West of the Cascade Mountains there is considerable rural land in southwest WA, the Willamette Valley of Oregon and Northwest Oregon but there is also considerably more metropolitan area than east of the mountains. A much greater percentage of the population lives in urban centers west of the mountains. The Portland, OR/ Vancouver, WA primary metropolitan statistical area (PMSA) had a population of 1,819,000 in July, 1998, while the Salem, OR PMSA had 330,000 people and the Eugene/Springfield, OR PMSA had 314,000 people (USCB, 2000).

Agriculture and forestry are important economic sectors throughout the basin. Table 2-4, compiled from the Interior Columbia Basin Ecosystem Management Project Supplemental Draft EIS (ICBEMP, 2000), compares employment in economic sectors from the Columbia Basin east of the Cascade Mountains with national averages. The table shows that agricultural services, mining, wood products manufacturing (SIC 24), and farm employment all exceed the national averages. Recreation, while not included in the table is estimated to generate about 4.5 % of employment in the ICBEMP area (ICBEMP, 2000).

Table 2-5, compiled from McGinnis et al (1996), Illustrates the employment by economic sector in the metropolitan counties in the Portland Oregon, area. Forestry and agriculture are also very important in these counties. Manufacturing, construction and service industries appear to be more important in these metropolitan counties than in the rural areas east of the mountains.

An important land use feature of the basin is that large areas of land are administered by governments. This is especially true east of the Cascade Mountains. This portion of the Basin comprises 144 million acres and 75 million of those acres are administered by the Forest Service or the Bureau of Land Management (ICBEMP, 2000).

Table 2-4 : Comparison of employment in economic sectors in the United States to the interior Columbia Basin east of the Cascade Mountains. Numbers in bold indicate that the basin average is higher than the national average.

Industry	United States (%)	Eastern Basin Average (%)[1]
Agriculture services	1.24	**2.20**
Mining	0.58	**0.59**
Construction	5.33	**6.09**
Manufacturing	12.63	10.27
SIC 24[2]	0.57[3]	**2.00**
Transportation	4.73	3.95
Trade	21.48	**21.96**
FIRE[4]	7.41	5.32
Services	30.44	25.54
Government (all)	14.24	**15.46**
State and local	10.88	**12.32**
Farm Employment	1.93	**6.56**

[1] Numbers are for the interior Columbia River Basin area assessed by the Interior Columbia Basin Ecosystem Assessment Project.

[2] SIC 24 - Standard Industrial Classification for lumber and wood products. Manufacturing number includes SIC 24.

[3]National SIC 24 data from 1990 data.

[4]FIRE - Finance, insurance and real estate.

Table 2-5 : Employment in economic sectors in the metropolitan counties near Portland, OR in 1991.

Industry	**Clackamas Co.**	**Columbia Co.**	**Multnomah Co.**	**Washington Co.**	**Yamhill Co.**
Agriculture, Forestry, Fish	4.5%	8.2%	0.6%	2.7%	10.2%
Mining	0.1%	0.3%	0.1%	0.1%	0.3%
Construction	8.9%	6.1%	6.0%	7.9%	7.6%
Manufacturing	12.5%	20.7%	11.8%	19.4%	18.0%
Transportation, Communication, Utilities	3.1%	9.8%	6.3%	2.6%	2.8%
Trade	22.7%	12.1%	17.4%	20.6%	12.3%
FIRE	7.5%	4.3%	8.4%	8.1%	7.2%
Services	29.0%	22.7%	35.5%	30.8%	28.3%
Government	10.4%	14.2%	11.0%	6.6%	11.3%
other	1.3%	1.4%	2.9%	1.0%	2.0%

3.0 WATER TEMPERATURE ASSESSMENT

3.1 General

Water temperature is an important water quality component of habitat for salmon and other cold water organisms. Water quality standards have been developed by the states and tribes specifically to protect cold-water aquatic life, including salmonids, in the Columbia and Snake Rivers. Salmonids evolved to take advantage of the natural cold, freshwater environments of the Pacific Northwest. Temperature directly governs their metabolic rate and directly influences their life history. Natural or anthropogenic alterations in water temperature can induce a wide array of behavioral and physiological responses in these fish. These fluctuations may lead to impaired functioning of the individual and decreased viability at the organism, population, and species level. Feeding, growth, resistance to disease, successful reproduction, sufficient activity for competition and predator avoidance, and successful migrations are all necessary for survival and as discussed in Chapter 4, can all be affected by temperature.

The water temperature regimes of the Columbia and Snake Rivers have been altered significantly by human development along the main stems themselves and throughout the basins. Natural ecosystem processes and characteristics are essential to maintaining the generally cool water temperature regime in which salmon evolved in the hot, dry summer climate of the Columbia Plateau and Snake River Plain. Some of the processes and characteristics that are essential to maintaining the temperature regimes of streams and rivers are climatic conditions, flow characteristics (e.g. velocity, width to depth ratio), riparian shade, advection of heat, groundwater input and hyporheic interchange in the alluvial sediments of the channel and flood plains. Riparian shade was probably not a significant factor on the main stems of the Columbia and Snake because of their width and propensity to flood, but it may have been a factor in localized areas, providing cool near shore refugia to fish during hot summer days. The other factors have played a role in the temperature regimes of the Columbia and Snake Rivers and have been affected by human development.

The dams on the Columbia and Snake Rivers have greatly altered the channel geometry of the rivers and thereby, the flow characteristics. Previous studies of the Columbia and Snake Rivers (Davidson, 1964; Jaske and Synoground, 1970; Moore, 1969; Independent Scientific Group[5], 1996) have identified the construction and operation of hydroelectric facilities as having a major impact on the thermal regime of the Columbia and Snake Rivers. Jaske and Synoground (1970) concluded that the construction of river-run reservoirs on the main stem of the Columbia River caused no significant changes in the average annual water temperature, but that the operation of Lake FDR, the reservoir behind Grand Coulee Dam, delayed the time of the peak summer temperature in the Columbia River at Rock Island Dam by about 30 days. Moore (1969) found that both Lake FDR and Brownlee Reservoir on the Snake River caused cooling in the spring and summer and warming in fall and winter. The Independent Scientific Group (1996) concluded that "main stem reservoirs in the Snake and Columbia rivers have created shallow, slowly moving reaches of shorelines where solar heating has raised temperature of salmon rearing habitat above tolerable levels" and that water temperatures in the Columbia River Basin have been altered by development and are, at times, suboptimal or clearly detrimental for salmonids.

The dams on the two rivers have also greatly simplified the complex and dynamic gradient of habitat types typical of the pre-dam rivers. The ISG describes three important spatial dimensions to a natural river system. The **riverine** system is a longitudinal continuum of runs, riffles and pools. The **riparian** zone is a lateral array of habitats from the middle of the main channel through various side and flood channels and wetlands to flood plains and the uplands of the valley wall. The **hyporheic** zone is a "latticework of underground (hypogean) habitats associated with the flow of the river through the alluvium (bed sediments) of the channel and the flood plains." (ISG, 1996) The dams flooded most of the riverine, riparian and hyporheic features of the natural lotic system, essentially creating a series of more simple lentic zones between dams with little spatial complexity. Critical habitat for salmonids existed in all three of the habitat types, but the hyporheic zone was also very important in the regulation of water temperature.

According to the ISG, water flow through the interstitial spaces of the hyporheic zone in the river bed and the flood plain and then back to the river plays an especially important role in salmon ecology. The hyporheic flow returning to the river bed is a source of oxygen for salmon eggs and a source of nutrients to produce food for salmon larvae, but more important to this discussion, hyporheic flow is an important moderator of water temperature. In comparison to surface temperatures, hyporheic flow is cool in the summer and warm in the winter (ISG, 1996). According

[5] The Independent Scientific Group comprised nine experts in fishery sciences commissioned by the Northwest Power Planning Council to (1) perform an independent review of the science underlying salmon and steelhead recovery efforts and Columbia River Basin ecosystem health, and (2) develop a conceptual foundation that could form the basis for program measures and basinwide fish and wildlife management.

to the ISG, hyporheic flow appears to be critical to the high desert rivers of the Columbia Plateau where late summer water temperatures may be too high for salmon. The hyporheic flow provides cool places in the river for salmon to seek refuge on hot summer days. The ISG stated that "alluvial reaches are arrayed along the stream continuum like beads on a string" (ISG, 1996). As such they provided areas of hyporheic return flows to the river that provided salmon with cool water refugia all along the river length.

Surface and groundwater flows tributary to the Snake and Columbia rivers are sources of advected thermal energy that have the potential for modifying the thermal energy budget of the main stem. Moore (1969) studied the impact of the Clearwater and Salmon rivers on the main stem Snake and the Kootenai and Pend Oreille rivers on the Columbia during 1967 and 1968. He found that the Clearwater and Salmon rivers cooled the Snake River during some of this period, but at no time did they produce a warming effect. Viewing the Snake as a tributary to the Columbia, Moore (1969) and Jaske and Synoground (1970) concluded that the advected thermal energy from the Snake River increased the temperature of Columbia River during the summer. Moore (1969) estimated that the maximum temperature increase was of the order of 1 ^{o}C during 1967 and 1968, while Jaske and Synoground (1970) estimated the annual thermal energy contribution of the Snake River to the Columbia River to be on the order of 4,000 megawatts. The Independent Scientific Group (1996) discusses temperature in the tributaries primarily as it relates to habitat in individual tributaries. The group concludes that high temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the main stem and tributaries, but does not discuss the impact of the tributaries on the thermal energy budget of the main stem.

Wastewater discharges are also sources of advected heat to the main stems. There are 105 point source discharges with individual National Pollutant Discharge Elimination System (NPDES) permits on the main stem of the Columbia. There are 152 point source dischargers with general NPDES permits. All of these point sources are very small in comparison to the river flow.

Nonpoint sources of thermal energy are a source of advected heat to the main stems. Nonpoint sources encompass all diffuse sources of heat to the basin. Typical nonpoint sources include heat added to streams because of the reduction of riparian vegetation, heat from changing the width to depth ratio of tributaries through the accretion of sediments in the stream channels, and heat from irrigation return flows. Agriculture, forestry, urban development and surface transportation can be important sources of nonpoint heat from the basin to the main stems if they are conducted in a manner that removes riparian vegetation or increases sediment input to the streams. The nonpoint thermal energy enters the main stems primarily from the tributaries.

Human activities also effect the temperature regime of streams by altering the flow regime. For example, agriculture, forestry, and urban development can develop impervious surfaces, drain acreage for cropping and remove vegetation that tends to facilitate retention of water in the watershed. These actions reduce the retention of water in the soil and groundwater and accelerate the flow of precipitated water to the stream system. As a result, the streams are flashy, receiving most of their flow shortly after precipitation. This reduces the amount of groundwater available to be released to the stream during hot, low flow periods: groundwater that tends to cool the stream. Use of surface and ground water for water supply tends to affect the stream flow and temperature regimes in the same manner.

All of these forces are at play in the temperature regimes of the Columbia and Snake main stems. The purpose of this temperature assessment is to characterize the temperature of the rivers in comparison to the water quality standards, and describe the linkages between the various sources and causes of heat and the rivers' response in terms of in stream water temperature.

3.2 Water Quality Standards

Water Quality Standards (WQS) for lakes, streams, rivers, wetlands and other surface waters are established by States and certain Indian Tribes under the federal Clean Water Act (CWA). Water Quality Standards define the water quality goals of a water body by designating the use or uses to be made of the water, by setting criteria necessary to protect the uses and by preventing degradation of water quality through antidegradation provisions. They play an important role in protecting the quality of the waters of the United States by establishing the target water quality for waste water discharges, watershed management plans and TMDLs. Three states and one Indian tribe have WQS standards promulgated pursuant to section 303(c) of the CWA that apply to the Columbia and Snake Rivers: Idaho, Oregon, Washington and the Confederated Tribes of the Colville Reservation. Another Indian tribe, the Spokane Tribe of Indians has WQS for the Columbia River that have been adopted by the tribe but not yet approved by EPA. The WQS for each state and tribe for the portions of the Columbia and Snake Rivers subject to this TMDL are summarized below:

Idaho

The WQS for Idaho are established in the Idaho Administrative Code, IDAPA 16.01.02, "Water Quality Standards and Wastewater Treatment Requirements." Section 130.02 establishes the designated aquatic life uses of the Snake River between the Salmon River and the Washington Border as cold water. Section 100.01.a defines cold water as "water quality appropriate for the protection and maintenance of a viable aquatic life community for cold water species." Section 250.02.b establishes the water quality criteria for temperature for the cold water aquatic life use designation as "Water temperature of twenty-two (22) ^{o}C or less with a maximum daily average of no greater than nineteen (19) ^{o}C."

Section 070.06 discusses natural background conditions: "Where natural background conditions from natural surface or groundwater sources exceed any applicable water quality criteria as determined by the Department, that background level shall become the applicable site-specific water quality criteria. Natural background means any physical, chemical, biological, or radiological condition existing in a water body due only to non-human sources. Natural background shall be established according to protocols established or approved by the Department consistent with 40 CFR 131.11. The Department may require additional or continuing monitoring of natural conditions."

Oregon

The WQS for Oregon are established in the Oregon Administrative Rules, OAR 340-041-0001 to OAR 340-041-00975, "State-Wide Water Quality Management Plan; Beneficial Uses, Policies, Standards, and Treatment Criteria for Oregon." The Snake River in Oregon from the OR/WA Border at river mile 176 to the Salmon River at river mile 188 is included in this TMDL. The WQS for that portion of the river are included in the section for the Grande Ronde Basin (OAR 340-041-0722). The beneficial uses most sensitive to temperature in that reach are "Salmonid Fish Rearing" and "Salmonid Fish Spawning." The temperature criteria applicable to the reach are, in relevant part:

> "To accomplish the goals identified in OAR 340-041-0120(11), unless specifically allowed under a Department-approved surface water temperature management plan as required under OAR 340-41-026(3)(a)(D), no measurable surface water temperature increase resulting from anthropogenic activities is allowed:
>
> (i) In a basin for which salmonid rearing is a designated beneficial use, and in which surface water temperatures exceed 64.0 ºF (17.8 ºC);
>
> (ii) In waters and periods of the year determined by the Department to support native salmonid spawning, egg incubation, and fry emergence from the egg and from the gravels in a basin which exceeds 55 ºF (12.8 ºC)....
>
> (vi) In stream segments containing federally list Threatened and Endangered species if the increase would impair the biological integrity of the Threatened and Endangered population;" (OAR 340-041-0725 (2)(b)(A).

The period of the year designated by the Oregon Department of Environmental Quality for the protection of salmonid spawning, egg incubation, and fry emergence in the Snake River is October 1 through June 30 (Oregon DEQ, 1998).

The numeric temperature criteria are established for the seven-day moving average of the daily maximum temperatures. If there is insufficient data to establish a seven-day average of maximum temperatures, the numeric criterion is applied as an instantaneous maximum (OAR 340-041-0006 (54)). A measurable surface water increase is defined as 0.25 ºF (OAR 340-041-0006 (55)) . Anthropogenic is defined to mean that which results from human activity (OAR 340-041-0006 (56)).

The segment of the Columbia River which serves as the OR/WA border is included in this TMDL and subject to OR WQS. It stretches from the mouth of the river to river mile 309. The temperature sensitive beneficial uses vary from segment to segment along that reach as shown in Table 3-1.

Table 3-1: Oregon designated uses along the Columbia River

Basin/Columbia River Miles	Anadromous Fish Passage	Salmonid Fish Rearing	Salmonid Fish Spawning	Shad and Sturgeon Spawning/Rearing
Lower Columbia / 0-86	X	X		
Willamette / 86-120	X	X	X	
Sandy / 120-147	X	X		
Hood / 147-203	X	X	X	X
Deschutes /203-218	X	X		
John Day / 218-247	X	X	X	
Umatilla / 247-309	X	Trout	Trout	

The temperature criterion applicable to the Columbia River in Oregon is in relevant part:

"To accomplish the goals identified in OAR 340-041-0120(11), unless specifically allowed under a Department-approved surface water temperature management plan as required under OAR 340-41-026(3)(a)(D), no measurable surface water temperature increase resulting from anthropogenic activities is allowed: ...

(ii) In the Columbia River or its associated sloughs and channels from the mouth to river mile 309 when surface water temperatures exceed 68.0 ^{o}F (20.0 ^{o}C)"

(iii) In waters and periods of the year determined by the Department to support native salmonid spawning, egg incubation, and fry emergence from the egg and from the gravels in a basin which exceeds 55 ^{o}F (12.8 ^{o}C)....

(vi) In stream segments containing federally list Threatened and Endangered species if the increase would impair the biological integrity of the Threatened and Endangered population;" (OAR 340-041-0205(2)(b)(A).

The period of the year designated by the Oregon Department of Environmental Quality for the protection of salmonid spawning, egg incubation, and fry emergence in the Columbia River is October 1 through May 31 (Oregon DEQ, 1998).

Salmonid spawning occurs in the lower Columbia River upstream of river mile 112. Chum salmon are known to spawn around the Ives Island complex down stream of Bonneville Dam and in the vicinity of Interstate 205. They spawn in November and December and the eggs incubate until April. Lower river brights (Chinook) are also known to spawn in the Ives Island area starting about mid-October. Therefore, the water quality criteria for the lower Columbia are as follows:

→ mouth to river mile 112

all year - 20.0 EC

→ river mile 112 to river mile 309

October 1- May 31 - 12.8 EC

June 1 - September 30 - 20.0 EC

Washington

The WQS for Washington are established in the Washington Administrative Code, Chapter 173-201A WAC, “Water Quality Standards for Surface Waters of the State of Washington.” Waters of the state are categorized in the Water Quality Standards into classes based on the character of the uses of each water body. The designated uses of the Columbia and Snake rivers most sensitive to temperature are salmonid migration, rearing, spawning and harvesting; and other fish migration, rearing, spawning and harvesting (WAC 173-201A-030). The most protected class on the Columbia and Snake rivers is “AA” or ‘extraordinary’ and this applies only to Lake Roosevelt. The rest of the river is grouped into class “A” or ‘excellent’ (WAC 173-201A-130). Under each of these classes, the temperature standard is applicable at any time of day or night. It applies toward fish protection in all portions of the rivers, including fish passage facilities and fish ladders within the dam structures.

Each class of water is assigned a daily maximum numeric temperature criterion. For class “AA” waters it is 16 EC and for class “A” waters it is 18 EC (WAC 173-201A-030). However, for the Columbia River below Priest Rapids dam and for the entire Snake River, a special condition applies which is two degrees higher, 20 ºC (WAC 173-201A-130).

The Washington standards also include narrative requirements associated with natural conditions. “Natural Conditions” for temperature means water temperatures as they are best assessed to have existed before any human-caused pollution or alterations. If the Snake or Columbia Rivers are found to have a natural condition higher than the criterion, no additional temperature pollution can be added that will result in raising that natural temperature more than 0.3 ºC. The wording of this portion of the standard indicates that the 0.3 ºC increment is a constraint on the cumulative impact of all dischargers (WAC 173-201A-020).

There are also constraints on incremental temperature increases when existing temperatures are below the numeric criterion In some segments these allowable increases are expressed as formulas to be applied to individual sources, while in others the allowable increases are expressed as a maximum value not to be exceeded by cumulative impacts. The numeric temperature criteria and narratives establishing the allowable incremental temperature increases, applicable to the Snake and Columbia Rivers in Washington, are summarized in Table 3-2.

Table 3-2: Washington water quality standards along the Columbia and Snake rivers

Water Body	***Criteria***
Columbia Main Stem from the coast to the Oregon/Washington Border	"Temperature shall not exceed 20 ºC (68 F) due to human activities. When natural conditions exceed 20 ºC (68 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ºC (0.5 F) nor shall such temperature increases, at any time exceed 0.3 ºC (0.5 F) due to a single source or 1.1 ºC (2.0 F) due to all such activities combined." WAC 173-201A-130(20)
Columbia Main Stem Priest Rapids Dam to OR/WA Border	"Temperature shall not exceed 20 ºC (68 F) due to human activities. When natural conditions exceed 20 ºC (68 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ºC (0.5 F) nor shall such temperature increases, at any time exceed T=34/(T+9)." WAC 173-201A-130(21)
Columbia Main Stem Priest Rapids to Grand Coulee	"Temperature shall not exceed 18 ºC (64.4 F) due to human activities. When natural conditions exceed 18 ºC (64.4 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ºC (0.5 F). Incremental temperature increases resulting from point source activities shall not, at any time, exceed t=28/(T+7). Incremental increases resulting from nonpoint source activities shall not exceed 2.8 ºC (5.4 F)." WAC 173-201A-130(21) and WAC 173-201A-030(2)
Columbia Main Stem Above Grand Coulee	"Temperature shall not exceed 16 ºC (60.8 F) due to human activities. When natural conditions exceed 16 ºC (60.8 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ºC (0.5 F). Incremental temperature increases resulting from point source activities shall not, at any time, exceed t=23/(T+5). Incremental increases resulting from nonpoint source activities shall not exceed 2.8 ºC (5.4 F)." WAC 173-201A-130(22) and WAC 173-201A-030(1)
Snake Main Stem from the Washington/Oregon Border to the Clearwater River.	"Temperature shall not exceed 20 ºC (68 F) due to human activities. When natural conditions exceed 20 ºC (68 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ºC (0.5 F) nor shall such temperature increases, at any time exceed 0.3 ºC (0.5 F) due to a single source or 1.1 ºC (2.0 F) due to all such activities combined." WAC 173-201A-130(98)(b)

Snake Main Stem from the Clearwater River to the Columbia River.	“Temperature shall not exceed 20 ^oC (68 F) due to human activities. When natural conditions exceed 20 ^oC (68 F) no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3 ^oC (0.5 F) nor shall such temperature increases, at any time exceed t=34/(T+9).” WAC 173-201A-130(98)(a)

t = the maximum permissible temperature increase measured at a mixing zone boundary

T = the background temperature as measured at a point or points unaffected by the discharge and representative of the highest ambient water temperature in the vicinity of the discharge.

Confederated Tribes of the Colville Reservation

The WQS for the Confederated Tribes of the Colville Reservation were promulgated by EPA at 40 CFR 131.135. These standards apply to the Columbia River from the northern boundary of the reservation downstream to Wells Dam. The Columbia River is designated as “Class I (Extraordinary)” from the Northern Border of the Reservation to Chief Joseph Dam and “Class II (Excellent)” from Chief Joseph Dam to Wells Dam. The designated uses most sensitive to temperature are “Fish and shellfish: Salmonid migration, rearing, spawning and harvesting: other fish migration, rearing, spawning and harvesting.” The temperature criterion for Class I waters is:

> “(D) Temperature - shall not exceed 16.0 ^oC due to human activities. Temperature increases shall not, at any time, exceed t=23/(T+5).
>
> (1) When natural conditions exceed 16.0 ^oC, no temperature increase will be allowed which will raise the receiving water by greater than 0.3 ^oC.
>
> (2) For purposes hereof, “t” represents the permissive temperature change across the dilution zone: and “T” represents the highest existing temperature in this water classification outside of any dilution zone.
>
> (3) Provided that temperature increase resulting from nonpoint source activities shall not exceed 2.8 ^oC, and the maximum water temperature shall not exceed 16.3 ^oC.”

The temperature criterion for Class II waters is:

> “Temperature - shall not exceed 18.0 ^oC due to human activities. Temperature increases shall not, at any time, exceed t=28/(T+7).
>
> (1) When natural conditions exceed 18.0 ^oC, no temperature increase will be allowed which will raise the receiving water by greater than 0.3 ^oC.
>
> (2) For purposes hereof, “t” represents the permissive temperature change across the dilution zone: and “T” represents the highest existing temperature in this water classification outside of any dilution zone.
>
> (3) Provided that temperature increase resulting from nonpoint source activities shall not exceed 2.8 ^oC, and the maximum water temperature shall not exceed 18.3 ^oC.”

Table 3.3 summarizes the criteria that apply to the Columbia and Snake Rivers.

Table 3.3: Summary of water quality criteria for the Columbia and Snake rivers

River Reach	Idaho	Oregon (7 day running ave of the daily maximums)	Washington (Maximum)	Colville Reservation (Maximum)
Snake: Salmon R to OR Border	19 C daily ave 22 C max	Oct 1 to June 30 - 12.8 C or natural July 1 to Sep 30 17.8 or natural		
Snake: Or Border to Clearwater R.	19 C daily ave 22 C max		20 C or natural + .3 C	
Snake: Clearwater to mouth			20 C or natural + .3 C	
Columbia: Can Border to Grand Coulee			16 C or Natural + .3 C	16 C or Natural + .3 C*
Grand Coulee to Chief Joseph			18 C or Natural + .3 C	16 C or Natural + .3 C
Chief Joseph to Wells			18 C or Natural + .3 C	18 C or Natural + .3 C
Wells to Priest Rapids			18 C or Natural + .3 C	
Priest Rapids to OR Border			20 C or Natural + .3 C	

OR Border to mouth		Oct 1 to May 31 - 12.8 C or natural 20 C or natural	20 C or Natural + .3 C	

* Applies from the Northern Boundary of the Colville Reservation (approximately River Mile 721) to Grand Coulee Dam

3.3 Existing Data

3.3.1 Data Availability and Quality

There is a considerable record of temperature data from the Columbia and Snake Rivers. McKenzie and Laenen (1998) assembled temperature data from 84 stations along the two rivers within the study area of this TMDL. They collected data from all the dams along the rivers, a number of stations monitored by the United States Geological Survey and numerous other stations. Some of the data sets are quite extensive. For example, temperature data collection at the Rock Island Dam scroll case has been continuous since 1933 when it was the only dam on the river. Likewise, temperature data collection at the Bonneville Dam scroll case has been continuous since 1938 when there were only 2 dams on the river. These two data sets are of particular importance because they may represent the only temperature data collected before the construction of storage reservoirs that regulate the flow of the river. There were no dams upstream of Rock Island Dam for 9 years and there were no dams within 300 miles of Bonneville Dam for 18 years. While these dams may have had some effect on temperature, these two data records may be the best indication of the temperature regime of the Columbia River before the dams were built.

While scroll case data represents the longest continuous temperature record along the river and may be the only data from the river before flow regulation by dams, it is not clear how well scroll case temperature measurements at each project represent in-river temperature in the vicinity. The scroll case is located within the interior of the dam, usually just upstream from the blades of the turbine. Water temperature is often measured at an outlet pipe from the scroll case, prior to its use for cooling water. An EPA team visited six dams on the Columbia, Snake and Clearwater Rivers (McNary, Ice Harbor, Lower Monumental, Little Goose, Lower Granite and Dworshak) to observe and evaluate the temperature monitoring stations. They “observed little or no consistency in type of measurement instruments, location of instruments, number of instruments, and quality control for instruments and recording. For this reason, the accuracy of scroll case temperature monitoring likely varies significantly between facilities” (Cope, 2001). This does not mean that the scroll case data should not be used. The quality of the data varies and it should be used cautiously, but these long records of scroll case data can provide valuable insights on the temperature regime of the river system.

McKenzie and Laenen (1998) found the Rock Island scroll case data to be among the better data sets from the mid-Columbia. They compared the Rock Island data to data made available by Pacific States Marine Fisheries Council collected in 1966, 1971, and 1972 at the forebay, spillway and mid channel and found no bias for either site. The minimum, median, and maximum variability between the two data sets was 0.0, 0.2, and 0.8°C. Figure 3-1 depicts the scroll case data from Rock Island Dam for 1933 through 1937. These data indicate that prior to flow regulation at Grand Coulee Dam, peak summer river temperatures exceeded the water quality criterion of 18 °C.

The other long historical temperature record is from the Bonneville Dam scroll case. Mackenzie and Laenen (1998) found this data to be “relatively good for the entire period, however they are stepped throughout and may not be representative of the river cross section.” They compared scroll case and tail race data from 1972-1997 and found the scroll case data to be about 0.5-1.5°C higher. The Bonneville data from 1938 through 1942 are depicted in Figure 3-2. Note that temperatures exceeded the Washington criterion of 20 °C and reached as high as 22 °C.

The extensive data base assembled by McKenzie and Laenen (1998) is difficult to use for analyzing and comparing temperature from site to site, because there is little consistency in station location or monitoring methods. Few of the sites have quality assurance objectives or followed quality control plans. Results can differ depending on the location of the sampling site. For example Figure 3-3 compares temperature data collected at Ice Harbor Dam on the Snake River from the scroll case and from stations in the fore bay and tail race in 1994. Note the differences in temperature at these stations throughout the monitoring period. These stations were not chosen at random. They were selected to specifically illustrate the point, but this kind of difference is not rare in the assembled data and must be an important consideration in using this data for analysis or model development. In using these data it is important to compare like stations along the river (eg scroll case to scroll case, fore bay to fore bay) and to use long records or repetitive examples when drawing general conclusions about temperature trends.

3.3.2 Water Quality Criteria Evaluation

A visual scan of the available data shows that the rivers get quite warm, exceeding water quality criteria all along their lengths in the summer. This is confirmed by the data that Mackenzie and Laenen (1998) collected from total dissolved gas monitoring stations at the dams. Table 3-4 shows the frequency and magnitude of water quality criteria exceedances at nine dams along the rivers. Frequency ranged from 0.1 at Wells Dam on the Mid-Columbia to 0.18 at Priest Rapids on the Mid-Columbia and Ice Harbor and Lower Monumental on the Snake. The average magnitude of exceedance ranged from less than a degree C at Wells Dam to almost 2.5 °C at Little Goose on the Snake River.

Table 3-4. Frequency and average magnitude with which observed temperatures exceed Oregon's and Washington’s water quality criterion at selected locations on the Columbia and Snake rivers. Observed temperatures are from the total dissolved gas monitoring program (McKenzie and Laenen, 1998)

Location	Exceeds Water Quality Criterion		Record Length
	Frequency	Magnitude	

Lower Granite Dam	0.15	2.04	5/30/88-9/17/96
Little Goose Dam	0.15	2.49	5/30/88-9/16/96
Lower Monumental Dam	0.18	2.10	5/29/88-9/17/96
Ice Harbor Dam	0.18	2.35	5/29/88-9/23/96
Wells Dam	0.10	0.87	4/18/93-9/2/97
Priest Rapids Dam	0.18	1.61	4/28/88-12/31/97
McNary Dam	0.17	1.65	4/2/85-12/31/97
John Day Dam	0.15	1.65	4/17/84-9/16/97
Bonneville Dam	0.14	1.39	4/3/86-11/2/97

Figure 3-4 and 3-5 portray the number of days that Washington, Oregon and Colville water quality criteria were exceeded all along the Columbia River in 1997 and 2000. The data for these figures was taken from McKenzie and Laenen, 1998 and the University of Washington DART Internet site. Figure 3-6 illustrates the water temperature along the Columbia River on August 8, 1995, August 16, 1996, and August 23, 1997. The white line represents water quality criteria. Washington and Colville criteria over lap in the upper river. Washington's criteria changes from 18 ^{o}C to 16 ^{o}C at river mile 590 and the Colville's criteria changes from 18 ^{o}C to 16 ^{o}C at river mile 545. Washington and Oregon criteria are both 20 ^{o}C in the lower river. Oregon's criteria applies on the lower river from river mile 303 to the mouth. Figure 3-7 shows the water temperature along the Columbia River on August 9, 2000. From these figures, based on existing data, it is clear that the entire Columbia River frequently exceeds water quality criteria.

Figure 3-8, 3-9 and 3-10 show the number of days that Idaho, Oregon and Washington water quality criteria are exceeded along the Snake River. These figures use the Idaho maximum criterion of 22 EC. That criterion is exceeded less frequently than the Oregon and Washington Criteria for the same river reaches.

Table 3-5 summarizes Idaho water quality criteria exceedances for the entire data set for the Idaho stations. This data was all taken from McKenzie and Laenen, 1998.

Table 3-5: Exceedances of Idaho's maximum criterion for water temperature along the Snake River.

Location	Sampling Begun	Sampling Ended	Exceedances of 22 ºC
Chalk Creek RM 188.2	7-12-91	4-2-96	22
River Mile 180	8-8-91	10-15-96	9
Cochrane Is. RM 178.2	7-11-91	9-4-95	44
River Mile 169.7	7-11-91	8-4-96	41
Billy Creek RM 164.6	9-27-91	12-31-95	46
Anatone, WA RM 167.2	10-1-59	9-30-93	798
River Mile 155.9	7-11-91	4-26-96	4

Figure 3-11 shows the locations of all the stations along the Columbia and Snake rivers that were sampled in the 1990s or later and have exceedances of water quality criteria. The figure includes the stations from McKenzie and Laenen, Washington's 303(d) list and the University of Washington, DART Internet site.

The existing Columbia and Snake River systems exceed the water quality criteria for temperature frequently throughout their lengths. However, the water quality standards of Oregon and Washington and the Colville Tribe state that the criteria are not to be exceeded due to human or anthropogenic activities. We have already shown that the water quality criteria were exceeded at Rock Island Dam and Bonneville Dam when they were the only dams on the Columbia River (figures 3-1 and 3-2). Assuming that the water temperatures at those dams when they were the only dams on the river are indicative of the temperatures with relatively few impacts from human activities (closer to the site potential temperatures) we can compare that temperature record to the existing river temperatures to see if the temperature regime has been altered.

3.3.3 Changes in the Temperature Regime at Bonneville Dam

Bonneville Dam is the dam furthest downstream and is likely to demonstrate any cumulative impacts on water temperature from the dams and other human activities upstream. Figure 3-12 provides information on the number of days that exceeded water quality criteria (20 EC) at Bonneville Dam. It compares two time periods: the eighteen years when Bonneville was the only dam on the river for 300 miles with the first eighteen years following construction of the last dam on the Columbia/Snake River System. The figure demonstrates a considerable increase in the number of days per year that criteria are exceeded. The mean number of days exceeding the criteria is four times greater (48.4 days versus 12.3 days) for the time frame after all the dams were constructed. Figure 3-13 shows the same information in a different way. The frequency of exceedance of the criteria was about 3% of the time during the period when Bonneville was the only dam for 300 miles and 13% of the time after all the dams were constructed. Kickert and Dauble (2002) also demonstrated an increase in the number of days per year in which water temperature at Bonneville Dam equaled or exceeded 21 EC from 1939 through 1999. Their logarithmic trend line ranges from just over 0 days per year exceeding 21 EC at the beginning of that period to just over 40 days per year in 1998 (Kickert and Dauble, 2002).

Figures 3-12 and 3-13 show that a difference exists in the number of days exceeding water quality criteria between the two time periods 1939-1956 and 1976-1993 but they do not explain the cause of the difference. It may be due to the presence of the dams and human activity or it may be due to other physical differences during the two time periods. Two obvious physical characteristics that govern water temperature are air temperature and flow in the river. Davidson (1964) reported that weather and river flow accounted for 81% to 85% of the variability in water temperature in the free flowing Columbia River at Rock Island Dam.

Table 3-6 compares air temperature at five locations during the two periods 1939-1956 and 1976-1993. Note that at two of the sites (Waterville and Wenatchee) average temperature, the number of days per year exceeding 80 EF and the number of days exceeding 90 EC were all greater during the second time period indicating that air temperature may be influencing the number of days per year that water temperature exceeds criteria. However, at the other three sites mean temperatures were less during the second period, days exceeding 80 EF was less and days exceeding 90 EF was less at two of the sites (Lind and Spokane) and very slightly increased at Goldendale.

Table 3-6: Mean air temperature (EF) and average number of days per year that air temperature exceeded 80 EF and 90 EF during the two periods 1939-1956 and 1976-1993 at five locations in the TMDL area.

	Waterville		**Wenatchee**		**Goldendale**		**Lind**		**Spokane**	
	39-56	76-93	39-56	76-93	39-56	76-93	39-56	76-93	39-56	76-93
Mean	55.2E	56.8E	61.7E	63.2E	61.2E	60.7E	62.2E	58.2E	58.2E	57.4E
Days > 80E	34.7	53.1	77.6	87.2	64.3	63.8	87	82	58.7	55.4
Days > 90E	4.2	13.1	24.2	32.1	17.7	18.4	33	29.5	15.9	13.3

The annual average of the daily average Columbia River flows at Grand Coulee for the two time periods are shown in figure 3-14. The summary statistics for these data for the two time periods are:

	1939-1956	1976-1993
Maximum	136298.4 CFS	132641.5 CFS
Minimum	71147.5 CFS	80343.0 CFS
Mean	110150.8 CFS	102136.3 CFS

Flow appears to have been somewhat lower during the second time period but the trend is not statistically significant. In a two-tailed Students's T Test, the probability that rejecting the null hypothesis would be wrong is 20%.

Neither mean air temperature nor mean river flow for the short time periods discussed here appear to account for the large increase in the number of days in which water temperature exceeded 20 ^{o}C. Davidson (1961) predicted that the dams on the Upper Columbia would increase the temperature of the river. During hot, dry summers he expected that the river temperature would increase as much as 5 ^{o}F in July and August and 1.5 ^{o}F in September between Chief Joseph Dam and Priest Rapids Dam. However Jaske and Goebel (1967) concluded that the low-head dams on the Columbia River main stem did not result in significant change in average river temperature.

3.3.4 Temperature at Rock Island Dam

Figure 3-15 provides information on the number of days that exceed water quality criteria at Rock Island Dam. It demonstrates that the frequency of exceedance of the water quality criterion was higher for the period 1933-1941 (0.133) when Rock Island was the only Dam on the mid-Columbia than for the first nine years after all the dams had been constructed, 1976-1984 (0.104). This relationship is just the opposite of the relationship at Bonneville. Figure 3-16 displays the number of days exceeding the criteria at Rock Island Dam for the entire record.

There does not appear to be a relationship in which the exceedance increased after construction of all of the dams as was the case at Bonneville. Davidson (1961) predicted an increase in temperature between Chief Joseph Dam and Rock Island Dam of 2 ^{o}F in July, 3 ^{o}F in August and 1 ^{o}F in September. Such an increase would not be expected to increase the number of days that criteria are exceeded as significantly as at Bonneville, if at all some years. In fact it was suggested at a public workshop that the temperature at Rock Island Dam could be used as a line of evidence regarding whether the temperature shift at Bonneville Dam is indeed due to dams and other activity in the water shed or is instead due to global warming. It was suggested that if Rock Island shows the same temperature pattern as Bonneville, climate change might be the explanation for the increase in number of days of exceedance. In fact the Rock Island data does not show the same patterns as the Bonneville data.

Table 3-7 compares air temperature at Waterville and Wenatchee during the two time periods 1933-1941 and 1976-1984. Note that at these two locations mean air temperature was slightly greater during the second period at Waterville and the same for both periods at Wenatchee. The number of days per year during which air temperature exceeded 90 EF and 80 EF increased during the second period at Waterville. At Wenatchee the number of days over 90 EF and over 80 EF both decreased slightly.

Table 3-7: Mean air temperature (EF) and average number of days per year that air temperature exceeded 80 EF and 90 EF during the two periods 1933-1941 and 1976-1984 at Waterville, WA and Wenatchee, WA.

	Waterville		**Wenatchee**	
	1933-1941	1976-1984	1933-1941	1976-1984
Mean	56.5E	56.7	63.2	63.2
Days > 80E	44	51	86	85.4
Days > 90E	5	11	33.7	30.9

There are only nine years during which there were no dams upstream of Rock Island. This is insufficient time to separate the effects of the dams versus the effects of air temperature or flow on water temperature. Even the eighteen years of data at Bonneville is insufficient given the great variability in air temperature, flow and water temperature. However, there is a growing body of information on climate change that indicates that periodic climatic regime shifts have effected inland stream water temperatures.

3.3.5 Climate Change

The possible effect of climate change on the Columbia River temperature regime can be further evaluated by examining water temperature in the Fraser River. The Fraser River is a large northern temperate zone river like the Columbia. It Drains 230,000 square kilometers (89,700 square miles) and is 1370 km long (849 mile) (Foreman et al, 2001). Average daily discharge at Hope, B.C. peaks at about 7000 cubic meters per second (247,249 cfs) (Foreman et al, 2001). Natural water temperature of the Fraser and Columbia Rivers would be expected to behave similarly in response to climate. If climate change is responsible for warming the temperature regime in the Columbia River, similar trends would be expected in the Fraser. Foreman et al (2001) conducted a retrospective analysis of flows and temperatures of the Fraser River. They found that average summer temperature at Hell's Gate east of Vancouver increased 0.012 ^{o}C per year from 1941 to 1998. This trend is not significantly different from zero at the 95% confidence level. From 1953 to 1998 they found the trend to be 0.022 ^{o}C per year. This is significant at the 98% confidence level. Foreman et al (2001) attribute most of the river warming to climatic effects. At Bonneville using the same data depicted in figures 3-12 and 3-13 the average temperature from July 1 to September 15 was 18.8 ^{o}C for the period from 1939-1956 and 20.5 ^{o}C for the period from 1976 to 1993. The 0.022 ^{o}C per year warming trend observed in the Fraser River would explain 48% of this difference of 1.7 ^{o}C if it were applicable to the Columbia River. The 0.012 EC warming trend would account for 26% of the difference.

Petersen and Kitchell (2001) evaluated the effects of climate regime changes on water temperature in the Columbia River. They suggested that “large-scale climatic oscillations, or regime shifts, have likely caused water temperature in the Columbia River to vary several degrees between 1933 and 1996" (Petersen and Kitchell,2001). They demonstrated warming trends in water temperature at Bonneville Dam from the period 1939-1956 to the period1976-1993 similar to the 1.7 EC temperature change reported here. For example the average daily water temperature they reported during the period August 16 - October 31 was 16.2 EC from 1938 to 1946 and 18 EC from 1978 to 1996; a difference of 1.8 EC (Petersen and Kitchell,2001). However, It is difficult to separate the effects of the climatic oscillations from the effects of the dams on water temperature at Bonneville Dam because these oscillations don’t coincide well with the 18 year time period during which Bonneville was the only dam in the lower Columbia and for which data exist or the 18 year time period immediately following the construction all of the dams on the Columbia River in the United States and the lower Snake River. The Columbia Basin Index which Petersen and Kitchell (2001) used to identify the oscillations in the Columbia Basin showed climatic regime shifts to have occurred in the middle of the two time periods we studied. A shift occurred in 1946-47, near the middle of our first period from 1939 to 1956. Another shift occurred in 1984-85, near the middle of our second period from 1976 to 1993. So both time periods contained cooler/wetter climatic regimes and warmer/dryer regimes. There is little information to evaluate whether the magnitude of the climatic regime shifts can account for the increases in water temperature or to separate the water temperature effects of the regime shifts from the effects of the dams. Petersen and Kitchell (2001) suggested water temperature modeling based on local weather might be useful in analyzing the effects of dams on river water temperature.

3.3.6 Temperature Gradients in the Reservoirs

Another assembly of temperature data was compiled by Karr et al (1998) for the Lower Snake River. They included data from 16 transects spaced along the river from just above the Clearwater River to just below the confluence of the Snake and Columbia Rivers. Karr et al also reported data collected from the fish ladders of the four lower Snake River Dams.

The transects were monitored in 1991 and 1992. Temperature measurements were taken at four depths and 3 specific locations across the river: near the surface, 1/3 depth, 2/3 depth and near the bottom at mid-channel, and 1/4 of the width from each bank. Table 3-8 was constructed from temperature contour figures presented in Karr et al (1998).

Table 3-8: Temperature near the surface and bottom of the lower Snake River reservoirs near each dam. The data was constructed from figures in Karr et al (1998).

	Lower Granite		**Little Goose**		**Lower Monumental**		**Ice Harbor**	
Date	**Surface**	**Bottom**	**Surface**	**Bottom**	**Surface**	**Bottom**	**Surface**	**Bottom**
08/08/91	22.2 C	21.1 C	23.8 C	21.1 C	23.3 C	20.5 C	25.5 C	21.1 C

08/23/91	22.2 C	17.7 C	22.7 C	22.2 C	22.7 C	21.6 C	23.3 C	22.2 C
08/27/91	21.1 C	17.7 C	21.6 C	19.4 C	21.6 C	21.6 C	21.6 C	21.6 C

This table illustrates water conditions near the dams before and after the release of cold water from Dworshak Dam on the Clearwater River just upstream of the Snake River. It shows the warm temperatures that can develop behind the dams, the temperature gradients that can develop with depth and the effects of the cold water releases on water temperature in the Snake River. On August 8, 1991, the water temperature exceeded the water quality criterion of 20 C throughout the water column near all of the dams. Further there was a temperature gradient between the surface and the bottom in the reservoirs ranging from 1 C near Lower Granite Dam to 4 C near Ice Harbor Dam. On August 16, 1991, the Corps of Engineers modified release of water from Dworshak Dam on the Clearwater River, to provide cool water to the Snake River. They released water at a temperature of 7.2 C at a flow rate of 10,000 cubic feet per second (CFS) from August 16, 1991 to August 22, 1991 (Karr et al, 1998). By August 23, 1991 the water released from Dworshak had cooled the deeper water near Lower Granite, creating a temperature gradient of over 4 C between the surface and bottom. It also appears to have had a cooling effect downstream, reducing the temperature gradients near the dams to no more than 1 C. The temperature still exceeded the water quality criterion near all the dams except Lower Granite. On August 27, 1991, the lower river had cooled more but the criteria were still exceeded in most places near the dams. Some of the transects not shown here exhibited greater cooling. Transect number 6 in the reservoir behind Little Goose Dam was below the criteria throughout its depth and transect number 7 also in the reservoir behind Little Goose Dam was below the criterion for most of its depth.

3.3.7 Temperature in the Fish Ladders

Karr et al (1998) also presented temperature data from the fish ladders at the Snake River Dams. Table 3-9, constructed from Karr (1998) data, displays the mean monthly temperatures in the fish ladders from 1991 through 1994. The temperature data was reported by Karr as °F and converted here to °C. The tail race station is outside of the fish ladder below the dam. The fish ladder temperature, like the tail race temperature varied considerably from year to year with 1991 and 1992 being warm years and 1993 and 1994 being cooler years. While the lower fish ladder temperatures were higher than the tail race temperatures in all but one of the cases where both data existed, the temperature difference between the two varied widely. In the one case when the tail race was warmer it was 1.8 °C warmer. The rest of the time the lower fish ladder varied from 0.1 °C warmer to 2.6 °C warmer. Water for the fish ladders is generally taken from the surface of the forebays, while the tailrace waters come from deeper in the reservoir. This may account for the warmer temperatures in the fish ladders.

In summary, there is an extensive data base for water temperature along the Columbia and Snake Rivers. We know from the data that the rivers are quite warm in the summer, with records that exceed the ID, OR and WA water quality criteria at times along their length. The earliest records from Rock Island Dam in 1933 and Bonneville Dam in 1938 include exceedances of the water quality criteria. In 1933 Rock Island was the only dam in the Columbia River. In 1938 Rock Island and Bonneville were the only two dams on the rivers. Data from Bonneville Dam indicates that the number of days with water temperatures over the state water quality criteria have increased significantly since the system of dams was constructed on the two rivers. The increased number of days that water quality criteria are exceeded after the dams were built is not explained by differences in air temperature or river flow. Data from Rock Island Dam does not show the same relationship. In fact, there does not appear to be any relationship at Rock Island Dam between the number of days each year that criteria are exceeded and construction of the system of dams on the rivers. The existing data record shows temperature gradients with depth in the reservoirs in the lower Snake River and it shows effects of cooling water from the Clearwater on the temperature gradients and the over all temperature of the lower Snake. Finally there is some temperature data from fish ladders at dams on the Lower Snake which shows that the ladders can get warm, at times warmer than the tail race temperature at the dams.

Table 3-9: Mean monthly temperatures of fish ladders at the four lower Snake River dams from 1991 through 1994. This table is taken from Karr et al (1998). The temperature was reported by Karr in ºF and converted here to ºC.

		1991			1992			1993			1
Dam	Month	Tailrace	Lower	Upper	Tailrace	Lower	Upper	Tailrace	Lower	Upper	Tailrace
Ice	Aug	22.4	23.9		20.8	22.0	22..1	19.4	19.8	20.1	19.5
Harbor	Sep	20.3	22.3	20.1	19.7	20.9	19.8	19.1	19.8	19.8	20.0
	Oct	16.1	18.7	17.6	15.7	16.0	15.9				17.2
Lower	Aug	22.4		22.7	20.7	21.7	21.9	19.1	19.7	20.2	18.4
Monu	Sep	20.8		20.6	21.2	19.4	19.8	19.4	19.7	20.0	20.1
Mental	Oct	15.7		15.9		15.5	15.7				
Little	Aug		22.6	22.8	21.1	22.2	22.3	19.1	20.0	20.0	18.5
Goose	Sep	19.3	20.1	20.2	18.9	19.2	19.1	20.1	20.6	20.5	20.6
	Oct	15.7	18.0	15.9	15.3	15.7	15.5				16.8
Lower	Aug	21.1	23.5	23.9	21.7	23.1	23.2	19.2	20.3	20.5	19.8
Granite	Sep	18.9	19.2	19.7	17.1	18.8	18.6	19.0	20.6	21.0	20.2
	Oct	15.9	18.1	16.8	15.3	15.8	15.8				16.3

3.4 Temperature Modeling

3.4.1 Introduction to the Model

EPA has developed a mathematical model to simulate temperature in the Columbia and Snake Rivers. This model, called RBM-10, is described in the report, “Application of a 1-D Heat Budget Model to the Columbia River System” (Yearsley, 2001). RBM-10 is a one-dimensional mathematical model of the thermal energy budget that simulates daily or hourly average water temperature under conditions of gradually varied flow. Models of this type have been used to assess water temperature in the Columbia River system for a number of important environmental analyses. The Federal Water Pollution Control Administration (Yearsley, 1969) developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River

Thermal Effects Study. The Bonneville Power Administration et al. (1994) used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the System Operation Review, and Normandeau Associates (1999) used a one-dimensional model to assess water quality conditions in the Lower Snake River for the U.S. Army Corps of Engineers.

RBM-10 uses real time meteorological and hydrological information to simulate water temperature in the river. In this case, 30 years of meteorological and hydrological data from 1970 to 1999 was used to simulate both the actual water temperatures for those years and the temperatures that would have occurred in the absence of human activity. This modeling strategy allows us to separate the effects of human activity in the main stems on water temperature from the effects of climate change on water temperature.

The ability of RBM-10 to simulate average temperature is discussed in Appendix D of the modeling report (Yearsley, 2001) and in a report updating the model description to reflect changes incorporated in the model since its development (Yearsley, 2002). Tables 3-10 and 3-11 summarize the differences between simulated and observed temperatures in the Columbia and Snake Rivers respectively.

Table 3-10: Summary of the differences between simulated temperature and observed temperature (simulated - observed) along the Columbia River.

Site	# of Samples	Absolute Mean Difference	Average Difference	Root Mean Square Difference	Standard Deviation
Grand Coulee	1150	0.731	-0.083	0.974	0.941
Chief Joseph	678	1.048	0.811	1.457	1.464
Wells	348	0.522	0.401	0.696	0.324
Rocky Reach	512	0.671	0.571	0.862	0.417
Rock Island	534	0.639	0.532	0.845	0.431
Wanapum	889	0.813	0.53	1.25	1.56
Priest Rapids	773	0.779	-0.09	1.033	1.058
McNary	1222	0.558	-0.339	0.719	0.402
John Day	666	0.455	0.015	0.594	0.353
The Dalles	703	0.427	0.057	0.541	0.289
Bonneville	493	1.066	-0.592	1.357	1.491

Table 3-11: Summary of the differences between simulated temperature and observed temperature (simulated - observed) along the Snake River.

Site	# of Samples	Absolute Mean Difference	Average Difference	Root Mean Square Difference	Standard Deviation
Lower Granite	1144	0.829	-0.644	1.033	0.652
Little Goose	746	0.771	-0.294	1.129	1.188
Lower Monumental	819	0.726	-0.186	0.925	0.82
Ice Harbor	1222	0.776	-0.299	0.934	0.783

The comparison of simulated and observed temperatures gives us an estimation of the accuracy of the model in simulating existing river conditions. It is not possible to develop a similar estimate for simulations of temperature in the absence of human activity because there are no observed values available for a comparison. Unless there are significant differences in the sources and sinks of heat between the existing river and the river without human activity, one would expect the model to accurately simulate either condition. There are at least two differences that might make the simulations different that need to be evaluated: unregulated flow and hyporheic flow.

Flow in the river now is regulated by storage reservoirs to prevent flooding and provide water for irrigation, power generation and navigation. The result is that flows generally do not get as low in the summer as they did before human development and they generally do not flood as much as they did before. The model simulations for both existing conditions and conditions without human development use regulated flows. They are regulated by reservoirs and other human activities upstream of this TMDL project area. The result of this is that the summer low flows in the model may not be as low as they would be without flow regulation. The river under lower flows would probably tend to heat up faster in the early summer and get warmer. However, the lower flows would also make the river cool faster in the late summer and fall.

Another change in the rivers since human development is the loss of hyporheic flow exchange. Before the rivers were dammed they had considerable alluvial flood plains as discussed in section 3.0. These flood plains absorbed flow into the gravelly hyporheic zone during high flows and released it to the river during lower flows. Now those flood plains are flooded year around and no longer exchange flows with the river. The model does not account for these flows under either the existing scenario or the no human activity scenario. Since these hyporheic flows tended to be sources of cool water during low flow periods, the model would tend to overestimate the temperature in these areas. Since the magnitude of the hyporheic flows is unknown, it is difficult to assess their effect on the overall temperature of the river. The Columbia is a very large river, and it would require considerable flow to noticeably affect the cross sectional average temperature of the river. However, even if they did not lower the overall cross sectional temperature, the hyporheic flows would have provided local cooling. These areas of localized cooling spaced along the river may have served as refuges for salmon.

3.4.2 Differences in the Temperature Regime with the Dams in Place

The model was run using 30 years of actual meteorological and hydrological data for both the existing conditions and conditions in the absence of human activity in the project area (dams taken out for the simulations). The hourly cross-sectional average temperature can be plotted against time for any location along the river. Figure 3-17 is an example of temperature with and without dams in place for 1992 at Ice Harbor Dam.

This figure illustrates that the impounded river stays warm in the late summer longer than the free flowing river and the temperature in the impounded river does not fluctuate in the short term as much as the temperature in the free flowing river. Temperature in the free flowing river fluctuates more diurnally and in response to meteorological conditions.

Figures 3-12 and 3-13 had demonstrated that the existing river at Bonneville Dam had four times as many days per year in excess of 20 ^{o}C than the river had before all the dams were constructed. One reason for this may be the fact that the impounded river cools much more slowly in the fall and does not fluctuate in response to short term changes in meteorology. Figure 3-17 shows considerably greater diurnal and short term fluctuation in the free flowing river. Figure 3-18 illustrates the relationship of the short term fluctuations to meteorology. It is from the same data set as figure 3-17 but shows only the warm part of the year and includes the air temperature at Lewiston ID. Each of the rather dramatic short term decreases in water temperature in the free flowing river was accompanied by equally obvious decreases in the air temperature at Lewiston. The impounded river was relatively unaffected by these decreases in air temperature.

3.4.3 Relative Impacts of Dams and Tributaries on Temperature

The model was further used to compare the relative impacts of the dams and advected heat from tributaries on the water temperature of the rivers. The objectives of this comparison were to assess the relative contribution of impoundments and tributary inputs to changes in the thermal regime of the Columbia and Snake rivers. To capture the environmental variability in hydrology and meteorology, the 30-year record of stream flows and weather data from 1970 to 1999 was used to characterize river hydraulics and surface heat transfer rates.

The assessment of impacts to the thermal regime of the Columbia and Snake River was based on the following three scenarios:

Scenario 1 This scenario includes the existing configuration of dams, hydrology, and meteorology from 1970 to 1999.

Scenario 2 This scenario assumes the Columbia River downstream from the Canadian Border and the Snake River downstream from the Salmon River are unimpounded and that hydrology, meteorology, and tributary temperatures are the same as Scenario 1.

Scenario 3 This scenario assumes the existing configuration of dams, with hydrology and meteorology for the period 1970 to 1999. Tributary input temperatures are not allowed to exceed 16 ^{o}C (60.8 ^{o}F).

For each of these scenarios, daily average water temperatures were simulated and compared to 20 ^{o}C (68 ^{o}F). A single benchmark of 20 ^{o}C was used to simplify this assessment of relative impacts from dams and tributaries. It should be noted that this assessment is preliminary to the TMDL, which must address the varying water quality criteria that apply to each river reach. The frequency of temperature excursions, calculated from the model simulations, establish a basis for assessing the relative impact of dams and tributary inflow on the thermal regime of the Columbia and Snake rivers. The mean frequencies of temperature excursions above 20 ^{o}C for each scenario as a function of Columbia and Snake River Mile are shown in Figures 3-19 and 3-20.

For the Columbia River in Scenario 1, the existing conditions with dams in place, the mean annual frequency of temperature excursions above 20 deg C remains close to 0 between Grand Coulee Dam (Columbia River Mile 596.6) and Priest Rapids Dam (Columbia River Mile 397.1). The influence of the warmer Snake River leads to an increase of the average frequency of excursions at McNary Dam (Columbia River Mile 292.0) of 0.06. Downstream from McNary Dam, the mean frequency of temperature excursions continues to increase to 0.1 at Bonneville Dam.

For the unimpounded case (Scenario 2), the mean annual frequency of excursions is similar to the impounded case upstream of the confluence with the Snake River. But below the Snake River, the frequency of excursion for the unimpounded river is much less than for the impounded river. For example, at Bonneville Dam the frequency is 0.06 for the unimpounded river and 0.1 for the impounded river.

The frequency properties of Scenario 3, for which tributary temperatures are constrained to be always less than 16 ^{o}C, are similar to Scenario 1 on the Columbia River upstream of its confluence with the Snake. The combined average annual flows of advected sources in this segment (Table 2-1) are less than 10 percent of average annual flow of the Columbia River at Grand Coulee Dam. The impact of these sources on the thermal energy budget of the main stem Columbia is, therefore, small. The 16 ^{o}C constraint was not applied to the Snake River, however, reductions in tributary temperatures in the Snake, particularly the Salmon and Clearwater rivers, results in a slightly lower mean frequency of excursion at Bonneville for Scenario 2 compared to Scenario 1.

In the Snake River, with dams in place (Figure 3-19), the mean frequency of temperature excursions is about 0.05 at the starting point (Snake River Miles 168.0), and increases to 0.17 between there and Ice Harbor Dam (Snake River Miles 9.0). For the unimpounded case (Figure 3-19), the analysis predicts that the mean frequency of temperature excursions increases much less between the starting point and Ice Harbor dam than the impounded case. At Ice Harbor Dam the frequency is about 0.1 for the unimpounded river and 0.17 for the impounded river. Scenario 3 shows that the water temperature of the Salmon and Clearwater rivers can effect the water temperature of the Snake.

Changes in cross-sectional daily average water temperature between initial conditions and some downstream point in rivers are due to (1) meteorology (wind speed, air temperature, cloud cover, air moisture content), (2) river depth, and (3) travel time between the two points. The meteorology determines the maximum temperature the water body can achieve; the depth and certain components of meteorology determine the rate at which the water body exchanges heat with the atmosphere; and the travel time determines the importance of initial conditions.

Some limits on the cross-sectional daily average water temperature in rivers can be estimated by defining the equilibrium temperature as the temperature a body of water would reach after very long exposure to a specific set of meteorological conditions. For a river moving with an infinitely high speed, the cross-sectional daily average water temperature at some downstream point will be exactly the same as the initial conditions. The meteorology would have no effect on cross-sectional daily average water temperature for this case. A water body at rest (no velocity) under constant meteorological conditions would eventually reach the equilibrium temperature determined by wind speed, air temperature, cloud cover, and air moisture content. The water depth and certain components of the meteorology would determine the time it takes to reach the equilibrium temperature.

The impact of structural changes on the cross-sectional daily average water temperature river system, such as the construction and operation of dams and reservoirs, is determined by the relative importance of the three factors described above. The results for Scenarios 1 and 2 imply that the structural changes associated with construction and operation of hydroelectric facilities on the Columbia and Snake rivers have led to changes in the travel times that are sufficient to modify the temperature regimes of these rivers.

The impact of advected sources such as tributaries and point discharges on the cross-sectional daily average water temperature of the main stem Columbia and Snake rivers is determined by the ratio of advected energy from the source to the advected energy of the main stem. Contribution of thermal energy of most of the advected sources (tributaries and point sources) is small due to the magnitude of their flow compared to the main stems. The Clearwater and Salmon rivers do have a significant cooling effect on the cross-sectional daily average water temperature of the Snake River. In addition, the Snake River has a significant warming effect on the cross-sectional daily average water temperature of the Columbia River.

3.5 Synthesis of Temperature Information

In the hot, dry summer climate of the Columbia Plateau and the Snake Plain it is important to look at the entire temperature regime in order to understand how these rivers support cold water fish like salmon. Important features of the temperature regime of the river include the maximum temperatures reached, the daily temperature fluctuations, the speed with which the water cools in the fall, the areas of cool temperature (refugia) provided by the alluvial flood plains, etc. While the role that these play in salmon ecology may not be fully known, they are each undoubtedly woven into the salmon survival strategy.

A synthesis of the information discussed in this chapter on existing temperature data and temperature modeling provides information about the natural and existing temperature regimes of the river:

- The temperatures of the Columbia and Snake rivers frequently exceed state and tribal water quality criteria for temperature during the summer months throughout the area covered by this TMDL.

- The water temperatures of the rivers before construction of the dams could get quite warm, at times exceeding the 20 ^{o}C temperature criteria of Oregon and Washington on the lower Columbia River.

- However, these warm temperatures were less frequent without the dams in place. Temperature observations show that the frequency of exceedance at Bonneville Dam of 20 ^{o}C increased from about 3% when Bonneville was the only dam on the lower river to 13% with all the dams in place.

- The dams appear to be a major cause of warming of the temperature regimes of the rivers. Model simulations using the existing temperatures of tributaries and holding tributary temperatures to 16 ^{o}C revealed that only the Salmon and Clearwater rivers affect average water temperature in the Snake and only the Snake affects water temperature in the Columbia.

- Climate change plays a role in warming the temperature regime of the Columbia River. The Fraser River, with no dams, shows an increasing trend in average summer time temperature of 0.012 ^{o}C/year since 1941, 0.022 ^{o}C/year since 1953. If applied to the Columbia, this would account for 26% to 48% of the temperature increase seen at Bonneville dam since 1939.

- The modeling strategy used here illustrates the effect dams have on water temperature independent of climate change. The warming effect of dams occurs in addition to the effects of climate.

- The average water temperatures of the free flowing river exhibited greater diurnal fluctuations than the impounded river.

- The free flowing river average water temperature fluctuated in response to meteorology more than the impounded river. Cooling weather patterns tended to cool the free flowing river but have little effect on the average temperature of the impounded river.

- The free flowing river water temperatures cooled more quickly in the late summer and fall.

- Alluvial flood plains scattered along the rivers moderated water temperatures, at least locally, and provided cool water refugia along the length of the rivers.

- The existing river can experience temperature gradients in the reservoirs in which the shallow waters are warmer.

- Fish ladders, which provide the only route of passage for adult salmon around the dams, can be warmer than the water in the tail race of the dams.

The goal for ameliorating temperature problems in the Columbia and Snake River main stems should be to restore as many of the natural characteristics of the temperature regime as possible. The TMDL will establish the heat reductions that will allow the bulk or thalweg temperature of the existing river to match the annual temperature cycle of the free flowing river. Meeting these reductions will correct some problems in the existing temperature regime. Essentially the daily temperatures will be more in line with natural daily temperatures throughout the year, including the late summer and fall. However, this will not necessarily eliminate the problems in important salmon habitats like the fish ladders and the shallow areas in the reservoirs. It also won’t necessarily restore the temporal fluctuations and the cold water refugia which provided cooling times and areas for salmon in the natural rivers.

4.0 Effects of Increased Water Temperature on Native Salmonids and Sturgeon

4.1 General

Chapter 3 of this problem assessment described the changes to the temperature regime of the Columbia and Snake rivers associated with the development of water resources. The purpose of this chapter is to evaluate the effect of water temperature on chinook salmon (*Oncorhynchus tshawytscha),* sockeye salmon (*O. nerka*), coho salmon (*O. kisutch),* steelhead trout (*O. mykiss*)*,* bull trout (*Salvelinus confluentus*), and white sturgeon (*Acipenser transmontanus*). Water temperature affects all life stages of these fish. It directly affects spawning, rearing, feeding, metabolic processes including growth, and overall survivability. Further, the incidence and intensity of some diseases are directly related to increased water temperatures. Indirect effects of increased water temperature include changing food availability, increasing competition for feeding and rearing habitat, and enhancing the habitat for predatory fishes.

The effects of increased temperature on spawning, growth, migrations (including smoltification), disease, predation, distribution, and other sub-lethal and lethal effects are addressed below in sections 4.2.1 to 4.2.7 for the three salmon species mentioned above and for the steelhead trout. The effects of increased temperature on bull trout and white sturgeon are assessed separately in sections 4.2.8 and 4.3.1, respectively. Since only adult bull trout are believed to periodically overwinter in the study area, the assessment will only consider the effects of increased temperature on growth, movement, and distribution for this life stage. Spawning and rearing for this species occur in cold-water tributary streams throughout the Columbia River basin (Ratliff & Howell 1992, Rieman et al. 1997). For the white sturgeon, only water temperatures needed for successful reproduction will be addressed. From our review of the literature, it appears that the time period for embryonic and early development is the most critical temperature-dependant life stage for the white sturgeon (Cech et al. 1984, Wang et al. 1987).

In the comprehensive literature review conducted for this assessment, an attempt was made to find and review all of the most important information available on the temperature-related factors affecting the salmonids mentioned above and the white sturgeon.

4.2 Salmonids

Native salmonid populations in the Columbia River basin have undergone serious declines resulting in the extinction of numerous runs. At present, 12 salmon and steelhead trout stocks in the basin are listed as threatened or endangered under the Endangered Species Act. Listed stocks located above Bonneville Dam are spring chinook and steelhead from the Upper Columbia River, steelhead from the Mid Columbia River, and spring/summer and fall chinook, sockeye and steelhead from the Snake River. Listed stocks below Bonneville Dam are chinook and steelhead from the Lower Columbia, chinook and steelhead from the upper Willamette River, and the Columbia River chum *(O. keta*). Native runs of coho and chum are extinct in the basin above Bonneville Dam, and below Bonneville their populations are depressed (Independent Scientific Group 1996, National Science & Technology Council 2000).

With regard to chinook salmon, spring-summer and fall races inhabit the basin. These races are also referred to as stream-type and ocean-type chinook salmon, respectively. The life cycles differ in that the spring-summer chinook usually rear in freshwater for one or more years, while fall chinook usually migrate to the ocean in their first year of life. Depending on growth rates, there may be exceptions to these migratory patterns. Slow growing fall chinook may outmigrate in their second year and fast growing spring-summer chinook may leave in their first year of life (Healey 1991). On first inspection, it would appear that spring-summer chinook would have the greatest potential exposure to increased water temperatures due to their longer freshwater residency, but they more commonly rear high in the tributaries that have cooler water and usually migrate to the ocean in the spring. In comparison, fall chinook spawn lower in the basin and migrate to the ocean in the late summer or early fall when water temperatures are at the highest point for the year (unpublished 2001 data from the Fish Passage Center).

To the extent that information is available, the effects of water temperature on the juvenile and adult life stages of chinook salmon, sockeye salmon, coho salmon, steelhead trout, and bull trout are summarized in Tables 4-1, 4-2, 4-3, 4-4, and 4-5, respectively. Life stages included in the juvenile classification are alevin, parr, fry, fingerlings, subyearling, yearling, and smolts. Adult studies include "jack" salmon, which are predominantly males that return early from the ocean and mature precociously. The effects of, or levels of concern for, water temperature listed in these tables are only for those life stages that occur within the study area. For example, fall chinook spawn in main channel areas in the basin, but other salmonids do not. Therefore, water temperatures that may cause increased mortality during egg incubation are provided only for fall chinook salmon.

4.2.1 Effects of increased temperature on spawning

Fall chinook salmon appear to be the only salmonid species that spawns in the main channels of the Columbia and Snake rivers. Except for limited main-stem spawning below Wanapum, Rock Island, and Wells dams in the Columbia River and below three of the lower Snake River dams (Dauble & Watson 1997), the main fall chinook spawning areas are located in the free-flowing Snake River below Hells Canyon Dam (Groves & Chandler 1999) and in the Hanford Reach (Dauble et al. 1989).

Fall chinook spawn from approximately mid-October to the third week of November in the Hanford Reach and from mid-October until mid-December in the Snake River. Water temperatures associated with spawning are similar for the two areas. Spawning occurs at daily mean temperatures ranging from 12 - 18.5 EC in the Hanford Reach (Dauble & Watson 1997) and at mean weekly temperatures ranging from 5 - 16 EC in the free-flowing Snake River (Groves & Chandler 1999). The higher temperature in each range occurs at the start of each spawning season after which the water temperature decreases during the winter incubation period.

Bell (1986) provides recommended spawning and incubation temperatures for nearly all salmonid fishes inhabiting the Columbia River basin. For fall chinook salmon, Bell (1986) recommends 5.6 - 13.9 EC and 5 - 14.4 EC, respectively, for spawning and incubation. The higher and lower values are threshold temperatures beyond which mortality increases.

A review completed by Hicks (2001) suggests that constant temperatures above 9 - 10 EC and below 5 EC may reduce the survival of chinook salmon embryos and alevins. For optimum protection from fertilization through early fry development, Hicks (2001) recommends that the weekly average of the daily maximum temperature at the time of fertilization not exceed 11 - 12 EC and that individual daily maximum temperatures not exceed 13.5 - 14.5 EC. These concerns and recommendations are repeated by McCullough et al. (2001) in a review of the same information.

Table 4-1: The effects of water temperature on chinook salmon.

Temp EC	Effect/Concern	Life Stage[1]	Reference
14-15	Increased egg mortality during incubation (fall chinook) Highest survival in hatcheries (<14 EC) Upper limit for optimum range Smolting impaired, migration stopped	Eggs A J J	Bell 1986, Hicks 2001 Leitritz & Lewis 1976 Brett 1952, Brett et al. 1982, Bell 1986 McCullough et al. 2001 Myrick & Cech 2001
16-17	Initial losses from diseases Handling stresses broodstock (>15 EC) Increased infertility, abnormal egg and embryological development	J-A A A	Fryer & Pilcher 1974, Fryer et al. 1976 Marine 1992 Marine 1992, Berman 1990 Hinze et al. 1956
18-19	Shallow water feeding areas abandoned Lethal chronic exposures	J A	Curet 1993, Connor et al. 1999 Marine 1992
20-21	Thermal barrier to migration Lethal chronic exposures Reduced or no growth Increased predation	A J J J	Hallock et al. 1970, Stabler et al. 1981 Beacham & Withler 1991 Brett et al. 1982, Harmon et al. 2001 Vigg et al. 1991, Vigg & Burley 1991
22-23	Lethal (22 EC), acclimated at 19 EC High disease mortality High mortality of hatchery releases	A J J	Coutant 1970 Holt et al. 1975 Baker et al. 1995

24-25	Lethal threshold (23.5-24.7 EC) Lethal (25 EC), acclimated at 20 EC	J J	Blahm & McConnell 1970 Brett 1952
26-28	High mortality in 24 hr after 67 minute exposure to 27 EC and return to 15 EC Increased predation after 67 second exposure to 28 EC and return to 15 EC	J J	Dean & Coutant 1968 Coutant 1973

Note: 1. J = juvenile, A = adult.

Table 4-2: The effects of water temperature on sockeye salmon.

Temp EC	Effect/Concern	Life Stage[1]	Reference
12-13	Migration reduced or stopped	J	Foerster 1937, Brett et al. 1958
14-15	Optimum for growth, swimming speed Maximum swimming speed Physiologically ideal in freshwater Optimum for river migration	J A J A	Brett et al. 1958, Bell 1986 Brett & Glass 1973 Brett 1967 Bell 1986

16-17	Initial losses from diseases Reduced reproductive capacity Outmigration ended, average temperature was 17.5 EC over 8 yrs	J-A A J	Ordal & Rucker 1944 Servizi & Jensen 1977 Bouck et al. 1975 Foerster 1937
20-21	Lose upstream orientation Migration blocked No or poor growth Increased predation	A A J J	Farrell 1997 Major & Mighell 1966 Donaldson & Foster 1941 Vigg et al. 1991, Vigg & Burley 1991
22-23	Lethal threshold (22.5-23.5 EC) Death in 2-5 days High mortality in 1 day, acclimated at 11 EC	J A J-KO[2]	McConnell & Blahm 1970 Servizi & Jensen 1977, Bouck et al. 1975 Black 1953
24-25	50% mortality with 6.7 hrs exposure, acclimated at 15 EC	J	Brett 1952

Notes: 1. J = juvenile, A = adult, 2. KO = Kokanee, a lacustrine stock of sockeye salmon.

Table 4-3: The effects of water temperature on coho salmon.

Temp EC	Effect/Concern	Life Stage[1]	Reference
12-13	Prevents premature smoltification (<12EC)	J	Wedemeyer et al. 1980
14-15	Optimum hypoosmoregulatory capacity Optimum growth (15 EC)	J J	Clarke & Shelbourn 1980 Jobling 1981
16-17	Initial losses from diseases Greatest growth (17 EC) Fish always present (MWMT[2] <16.3 EC)	J J J	Fryer & Pilcher 1974, Fryer et al. 1976 Clarke & Shelbourn 1980 Welsh et al. 2001
18-19	Fish may be absent (MWMT <18.1 EC)	J	Welsh et al. 2001
20-21	Sublethal stress (diel exposure 6.5-20 EC) Serious loss from disease Very restricted peak in gill ATPase Optimum cruising speed Fish absent or rare in stream (21 EC) Increased predation	J J J J J J	Thomas et al. 1986 Fryer & Pilcher 1974, Fryer et al. 1976 Zaugg & McLain 1976 Brett et al. 1958 Frissell 1992 Vigg et al. 1991, Vigg & Burley 1991
22-23	Fish used cold-water refugia Lethal threshold (23.5 EC)	J J	Bisson et al. 1988 Blahm & McConnell 1970

24-25	Upper lethal temperature 25 EC Lethal exposure 46 min at 26 EC	J A	Brett 1952, DeHart 1974 Coutant 1969

Notes: 1. J = juvenile, A = adult, 2. Maximum weekly maximum temperature.

Table 4-4: The effects of water temperature on steelhead trout.

Temp EC	Effect/Concern	Life Stage[1]	Reference
12-13	Exceeds upper limit of optimum range Smolting inhibited, migration reduced	J J	Bell 1986 Zaugg et al. 1972, Zaugg & Wagner 1973
14-15	Impaired adaptation to seawater Decline in gill ATPase	J J	Myrick & Cech 2001 Adams et al. 1973
16-17	Initial losses from diseases	J	Fryer & Pilcher 1974, Fryer et al. 1976
18-19	Habitat reduced by competition Growth rate declines (>19 EC) Fish used cold-water refugia	J RB[2] J-RB	Reeves et al. 1987 Myrick & Cech 2001 Frissell 1992
20-21	Migration delayed, fish used refugia High disease mortality Increased predation Reduced growth via competition	A J J J	Fish & Hanavan 1948, Stabler 1981 Holt et al. 1975 Vigg et al. 1991, Vigg & Burley 1991 Reese & Harvey 2002
22-23	Upper lethal limit Serious loss from disease	A J	Templeton & Coutant 1970 Fryer & Pilcher 1974
24-25	Upper lethal limit (24 EC) Chronic lethal level (>25 EC)	J J	Bell 1986 Myrick & Cech 2001

Notes: 1. J = juvenile, A = adult, 2. RB = Rainbow trout.

Table 4-5: The effect of water temperature on bull trout.

Temp EC	**Effect/Concern**	**Life Stage**[1]	**Reference**
10-12	Maximum growth Spawning movements to tributaries Highest density in streams (7.8-13.9 EC) Higher fitness trends	A-J A J A	Buchanan & Gregory 1997 McMahon et al. 1998 Fraley & Shepard 1989 McPhail & Murray 1979 Saffel & Scarnecchia 1995 Haas 2001
13-14	Out competed by sympatric salmonids	J A	McMahon et al. 1999 Haas 2001
15-17	Fish not present (>14 EC) Decreased fitness (>14 EC) Limits distribution (>15 EC) Thermal block to migration (16 - 18 EC)	A-J J A A	Goetz 1997 McMahon et al. 1998 Shepard et al. 1984 Thiesfeld et al. 1996 Shepard 1985
18-20	Lowest density in streams (18.3-23.3 EC) Reduced feeding efficiency and exhibited signs of stress Used thermal refugia 47% mortality in 60-day exposure (20 EC) 21% mortality in 60-day exposure (20 EC)	J J A Age-1 Age-0	Saffel & Scarnecchia 1995 Selong et al. 2001 Adams & Bjornn 1997 McMahon et al. 1999 Selong et al. 2001

21-22	54% mortality in 60-day exposure (21 EC) 100% mortality in 60-day exposure (22 EC) Transition trout to non-trout fish community	Age-1 Age-0 J-A BT[2]	McMahon et al. 1999 Selong et al. 2001 Taniguchi et al. 1998

Notes: 1. J = juvenile, A = adult, 2. BT = brook trout.

4.2.2 Effects of increased temperature on growth

Since growth is an integrator of environmental, behavioral, and physiological influences affecting fish, it is a very useful indicator of stress (Jobling 1996). Increased temperature has a profound influence upon growth rates, but the rates are also affected in a field environment by food availability, competition, and other factors. Numerous studies have inferred that if food is abundant in the wild, salmonid growth can be enhanced with increasing water temperature. Conversely, if food is limited, then any substantial temperature increase would result in decreased growth. The growth studies reviewed for this assessment were conducted on captive fish that were fed at levels up to satiation and that lacked the stresses typically found in a field environment. These limitations are important when considering the effects of increased temperature on fish growth using only laboratory studies. Intuitively, we expect lower growth rates to occur in the field given all of the energy requirements that fish need to compete for food and habitat, avoid predators, and to complete migrations to the ocean.

Our review of laboratory and hatchery studies indicates that growth declines or stops for juvenile chinook, sockeye and coho salmon and steelhead trout as water temperature increases into the 18 - 21 EC range. Optimum growth for these species occurs from about 15 - 17 EC (Brett et al. 1969, Banks et al. 1971, Brett 1971, Wurtsburg & Davis 1977, Clark & Shelbourn 1980, Jobling 1981, and Brett et al. 1982).

The above listed fish species are able to survive beyond these optimum ranges; however, growth is eventually reduced. At the higher temperatures most of the food is used for maintenance as metabolic rates are increased (Bjornn & Reiser 1991). Brett et al. (1982) and Thomas et al. (1986) report, respectively, sub-lethal growth stress for chinook at 18.5 - 21 EC and for coho exposed to diel fluctuations of 6.5 - 20 EC. Edsall (unpublished data referenced by the Great Lakes Fishery Laboratory 1970) observed declining growth as water temperature increased to 18 - 20 EC with immature coho salmon that were fed to satiation. Similarly, Donaldson & Foster (1941) noted slight or no growth in sockeye salmon held at 21.1 EC, and loss of weight and mortality at 22.8 EC. Wurtsburg & Davis (1977) studied the effects of temperature, ration level and fish size on juvenile steelhead growth. They measured maximum growth at 16.4 EC and noted that above this temperature growth rates declined rapidly.

Since the steelhead is an anadromous rainbow trout, we also reviewed temperature-limiting growth studies for the rainbow trout. For two strains of resident rainbow trout in northern California, Myrick & Cech (2001) found that growth rates increased with temperature to a maximum near 19 EC and declined rapidly at temperatures above 19 EC. In a series of growth experiments at seven constant and six diel fluctuating temperatures using rainbow stocks from Lake Superior, Hokanson et al. (1977) found that maximum growth occurred at 17.2 EC for the constant temperature treatments which ranged from 8 - 22 EC. For the fluctuating treatments with daily means of 12 - 22 EC and average amplitudes of ∀ 3.8 EC, maximum growth occurred at a mean temperature of 15.5 EC. Fish exposed to the highest diel fluctuation actually lost weight. All fish were fed to satiation.

4.2.3 Effects of increased temperature on migrations, including smoltification

Two migrations occur during the life cycle of anadromous salmonids. Juveniles migrate to the ocean and after an ocean rearing phase the adults return to their natal streams to spawn. The juveniles undergo parr-smolt transformation (or smoltification) during their journey to the sea. Smoltification is a physiological process that enables a fish to live in salt water, and involves changes in growth, condition factor, body silvering, body moisture and lipid content, and salinity tolerance (Wedemeyer et al. 1980, McCullough et al. 2001). Research conducted on this process has evaluated the concentrations of the gill enzyme ATPase and hypoosmoregulation. Reduced ATPase levels and impaired osmoregulation may result in delayed or ineffective transition to marine waters. With most anadromous salmonids, photoperiod or fish size appear to be the main drivers of smoltification, but water temperature can affect and halt this process including outmigration (Wagner 1974, Zaugg 1981). Bjornn & Reiser (1991) observed that the parr-smolts transformation is often incomplete when the fish begin to migrate and may fail to develop fully if the fish encounters high temperatures and reservoirs without perceptible currents.

The results of our literature review and the reviews of others indicate that the salmonid smolting process is adversely affected when temperatures reach a threshold level of 12 - 13 EC, and that outmigration may be stopped when water temperatures increase to 15 - 17 EC.

In an overall review of the salmonid smolting requirements, McCullough et al. (2001) conclude that these fish experienced reduced ATPase levels at temperatures greater than 11 - 13 EC. They also note that temperatures of 14 - 15 EC may stop outmigration. Another review by Wedemeyer et al. (1980) found that 12 - 13 EC is a threshold beyond which the smolting process for chinook and coho salmon and steelhead trout is disrupted or halted. A review by Myrick & Cech (2001) that focused on central California chinook salmon and steelhead populations found that temperatures greater than 15 - 16 EC impaired smoltification and salt water survival.

The following laboratory research further defines temperature levels affecting smoltification and outmigration. Clarke & Shelbourn (1985) found that freshwater rearing temperature and time of transfer are the most important factors influencing the ability of juvenile fall chinook salmon to regulate plasma sodium concentrations and grow in sea water. Osmoregulatory preadaptation to sea water was best when fish reared in 10 - 17.5 EC freshwater were transferred to sea water from early May onwards. Clarke & Shelbourn (1980) observed the greatest hypoosmoregulatory capacity in coho salmon at 11 - 15 EC. Brett et al. (1958) found that 12 - 14 EC stopped the downstream migration of juvenile sockeye salmon. Zaugg & Wagner (1973) found that steelhead trout had decreased ATPase and reduced migration at temperatures at and above 13 EC.

An 8-year field study by Foerster (1937) on juvenile sockeye salmon in Cultus Lake, BC revealed that as the surface temperature of the lake approached 13 EC outmigration of native fish decreased greatly. Thereafter only stragglers appeared in the migration, which stopped completely when the temperature reached 14 - 20 EC (averaged 17.5 EC).

Adult salmonid migrations back to their natal streams are also affected by water temperature. Water temperatures that enable upstream migration to occur are 10.6 - 19.4 EC for fall chinook, 3.3 - 13.3 EC for spring chinook, 13.9 - 20 EC for summer chinook, and 7.2 - 15.6 EC for sockeye (Bell 1986). Delays in upstream migration because natal streams are too warm have been observed for all of the salmonid species being considered in this assessment. These migrations appear to be impaired or blocked when water temperatures exceed 21 EC (Fish & Hanavan 1948, Major & Mighell 1966, Hallock et al. 1970, Monan et al. 1975, Stabler 1981, and Farrell 1997).

A comprehensive review by McCullough et al. (2001), found that migration blockages occur consistently among salmonid species in the temperature range 19 - 23 EC. The adults cope with the increased water temperatures during migration by using thermal refugia (Fish & Hanavan 1948, Berman & Quinn 1991, Nielsen et al. 1994), but this delay in their upstream migration may subsequently affect their reproductive capacity.

4.2.4 Effects of increased water temperature on the virulence of fish diseases

Water temperatures in many rivers in the Pacific Northwest from May through October are in a range favorable for the development of important salmonid infectious diseases (Fryer et al. 1976). These diseases, which are the result of bacterial, viral, or parasitic infections, can adversely affect juvenile and adult fish populations. Within the study area, sympatric fish species that are resistant or have survived past infections are the likely source of infection. When environmental conditions including water temperature become optimal, the disease may infect a susceptible host, grow and may become virulent. In a review of the effects of freshwater pathogens on wild and captive salmonid populations, Hicks (2001) arrived at the following conclusions: average temperatures below 12 - 13 EC significantly and often completely eliminate both infection and mortality, average temperatures above 15 - 16 EC are often associated with serious rates of infection and mortality, and average temperatures above 18 - 20 EC are commonly associated with very serious infections and often catastrophic outbreaks of many diseases.

With some exceptions, the results of numerous laboratory and field studies generally support Hicks' findings. Laboratory-induced infections of juvenile coho and spring chinook salmon and juvenile steelhead with ceratomyxosis (*Ceratomyxa shasta*) and columnaris (*Flexibacter columnaris*) follow this pattern (Fryer & Pilcher 1974, Udey et al. 1975, Fryer et al. 1976, Groberg et al. 1978). This same pattern is supported by a field study from the Fraser River, where Ching & Munday (1984) observed 95% mortality due to ceratomyxosis in 6 stocks of juvenile chinook salmon naturally infected during a 10-day exposure period at a mean temperature of 16.9 EC. An exception may be found in a study that exposed spring chinook, coho, and sockeye salmon to *C. shasta* while being held captive in the Willamette River (Zinn et al. 1977). These three species incurred low to moderate mortality during an exposure at temperatures ranging from 14.5 - 17 EC.

For adults, high mortality in laboratory-held spring chinook salmon at 17.5 - 19 EC and sockeye salmon at 20 EC was observed due to columnaris infections (Berman 1990, Bouck et al. 1975). Also, Colgrove & Wood (1966) observed that columnaris disease seldom occurred in adult sockeye salmon at temperatures below 12.8 EC, and that temperatures above 15.6 EC appeared necessary to initiate the pathological effects of the disease. Finally, Mackie et al. (1933) report that water temperatures must be greater than 12.7 EC for a serious furunculosis epizootic to occur in nature.

Any recommendation for temperatures to control fish disease should consider the effect of other stressors affecting the virulence of the disease. For example, Maule et al. (1989) noted that juvenile chinook salmon had lower resistence to infection and decreased ability to mount an immune response following an acute stress exposure. Also, different strains of a given disease may be more or less virulent (e.g., columnaris in juvenile sockeye salmon, Pacha & Ordal 1970), virulence may not be closely related to water temperature (e.g., bacterial kidney disease in juvenile coho salmon or steelhead, Fryer et al. 1976), or virulence may be highest at low temperatures (e.g., *Cytophaga psychrophila* in juvenile coho salmon, Ordal & Pacha 1963).

4.2.5 Effects of increased temperature on predation

Increased predation associated with rising water temperatures in the Columbia River basin is mainly an issue with downstream migrating juvenile salmonids. Water temperature has both direct and indirect effects on predation. Direct effects are realized when fish are weakened or shocked by high temperatures and become more susceptible to predation. Indirect effects occur when migratory pathways used by juvenile salmonids become more suitable for warm-water predators, when shallow water rearing areas become too warm for juvenile fish and they move into deeper water inhabited by predators, or when fish are weakened by diseases made more virulent by increased temperatures and become easier prey than healthy fish.

Limited information is available on shock effects caused by high water temperatures, and most of this research was done to assess salmonid survival in thermal discharges. At high water temperatures fish can lose their equilibrium in the water column and become easy prey. Coutant (1973) found that juvenile chinook salmon exposed to 28 EC for 1.1 to 5.6 minutes (10 to 50 % of the duration needed to cause complete loss of equilibrium) resulted in increased predation after the fish were returned to 15 EC. It may be difficult, however, to relate these exposures to environmental conditions in the reservoir system of the Columbia and Snake rivers where such steep (i.e., 13 EC) changes in temperature probably do not occur. Nonetheless, this study is demonstrative of an effect that may occur at lower temperature differentials.

As the water in the main channels and reservoirs of the Columbia and Snake rivers increases above 16 EC each summer, habitat conditions for predatory fish species improve. The northern pikeminnow (*Ptychocheilus oregonensis)*, walleye (*Stizostedion vitreum*), smallmouth bass (*Micropterus dolomieu*), and channel catfish (*Ictalurus punctatus*) are important fish predators inhabiting the reservoirs; but the pikeminnow is clearly the major predator on juvenile salmonids (Vigg et al. 1991, Mesa 1994). The preferred temperature ranges for the northern pikeminnow, walleye, smallmouth bass and the channel catfish are 16 - 22 EC, 21 - 23 EC, 20 - 21.7 EC and >21 EC, respectively (Vigg et al. 1991, Bell 1986). The prey consumption rates for these predators were highest in John Day Reservoir in July concurrent with maximum water temperature and the highest abundance of juvenile salmonids (Vigg et al. 1991). In tests conducted by Vigg & Burley (1991), peak consumption of juvenile salmonids by northern pikeminnow was near 21.5 EC, but these authors recommended further work to better define optimum temperatures for consumption and growth.

Increased water temperatures in shallow habitats is also an area of concern. Some juvenile salmonids feed in shallow water areas that have protective cover from predators on the margins of the Columbia and Snake rivers, including the reservoirs. As the water temperature increases in these areas they become less hospitable for juvenile fish, which then move into cooler, deeper water lacking cover and where predators are more common. Curet (1993) and Connor et al. (1999) noted subyearling chinook salmon moved from shoreline to pelagic areas in the Snake River when water temperatures increased to 17 - 19 EC; however, they did not document that this caused increased predation.

Predation of fish weakened by disease made more virulent by increasing water temperatures is likely secondary to the concern for the actual loss of fish due to the disease. Once fish are infected by a disease, recovery may not occur unless the water temperature drops. Nonetheless, sublethal infections may cause fish to be more prone to predation than healthy fish. Mesa et al. (1998) observed that juvenile chinook salmon infected with bacterial kidney disease (*Renibacterium salmoninarum*) were eaten by either northern pikeminnow or smallmouth bass in significantly greater numbers than control fish by nearly two to one.

Fish affected by multiple stressors in combination with high water temperature are also likely to be more susceptible to predation. In laboratory studies, Mesa (1994) found that juvenile chinook salmon subjected to multiple handlings and agitations became lethargic and more prone to predation by northern pikeminnow. Multiple stresses are more likely to occur when juvenile salmonids pass through dams during their outmigration. Increased water temperatures are commonly observed in the forebay areas of dams and the fish are then subjected to the stresses of being routed through the fish bypass structures or withstanding the pressure differentials as they negotiate passage through the turbines.

4.2.6 Effects of increased temperature on fish distribution

The distribution of native salmonids in aquatic habitats is strongly tied to natural thermal regimes, which in the Columbia River basin have been significantly modified by past anthropogenic influences such as dam construction and operation and water withdrawals. Natural shifts in the regimes like droughts have only added to the adverse effects of increased water temperature. When water temperatures exceed the preferred or optimal ranges for salmonids, their distribution is usually restricted. Laboratory studies have demonstrated that temperature alone can control the distribution of fish (Ferguson 1958), and that fish density within their habitats can be reduced at higher temperatures (Hahn 1977).

Juvenile coho salmon prefer a temperature range of 12 - 14 EC, which is close to optimum for maximum growth efficiency (Brett 1952). Several field studies have demonstrated the reduction in coho distribution when water temperature exceeds this optimum range. Two studies in the Sixes River basin in southwest Oregon found that juvenile coho were rare or absent in stream reaches that exceeded 20 - 21 EC (Stein et al. 1972, Frissell 1992). In a study of 21 tributaries of the Mattole River in northern California, Welsh et al. (2001) noted that juvenile coho salmon were always present when the average and maximum daily temperatures over a 7-day period (maximums for the entire summer) were <14.5 EC and <16.3 EC, respectively. At higher temperatures, the same study found that coho are usually restricted from tributaries when these average and maximum temperatures are >16.8 EC and >18.1 EC, respectively. In a study of three streams affected by the Mt. St. Helens eruption, Bisson et al. (1988) found that planted juvenile coho lived in streams where the average daily minimum temperatures ranged from 11 - 15 EC and maximum temperatures ranged from about 15 - 24 EC during July and August. Survival or retention of the planted fish ranged from 5.9 to 48.8% in these streams, but those that stayed grew at rates comparable with those in similar sized streams in the region. The results of these studies tend to support Brett's (1952) preferred temperature range, but they also show that in some cases coho can withstand higher temperatures but at reduced population numbers. At higher temperatures other factors such as unlimited food and lack of competition may enable these fish to survive.

The upper limit of the preferred range for juvenile chinook salmon is also about 14 EC (Brett 1952, Bell 1986). However, in sympatric relationships with coho, juvenile chinook salmon appear to be able to withstand higher temperatures. As the temperature of the Sixes River (Oregon) increased above 20 EC, chinook continued to reside after coho had departed (Stein et al. 1972), but 23 EC may be the maximum temperature for limiting their distribution in this river (Frissell 1992). Other studies, however, indicate the distribution of juvenile chinook salmon is affected at much lower temperatures. As previously mentioned, shallow water feeding areas in the Snake and Columbia rivers appear to become unacceptable to subyearling chinook salmon when the temperature in these areas exceeds 17 - 18 EC (Becker 1973, Curet 1993, Connor et al. 1999).

The upper limit of the optimal range for juvenile steelhead trout is 12.8 EC (Bell 1986). This species, however, may be able to successfully live at higher water temperatures in the southern part of its range. Cech & Myrick (1999) found that juvenile Nimbus strain steelhead, a fish native to California, has a higher thermal preference over a 11 - 19 EC range. At water temperatures of 19 - 22 EC, the distribution of steelhead in more northern parts of its range can be reduced by competition from non-salmonid sympatric fish species (Reeves et al. 1987).

4.2.7 Other sub-lethal and lethal effects of increased water temperature

Sub-lethal effects, not previously discussed, include impaired reproduction, neuro-endocrine and endocrine reactions, disturbances in osmotic and ionic regulation, and modified behavior. Lethal effects from increased water temperature can be acute, causing death in hours, or chronic, which causes death to occur over a longer period of time. Comprehensive reviews of sub-lethal and lethal effects of high temperature exposures on salmonids have been completed by Brungs & Jones (1977), Bell (1986), Marine (1992), Berman (1998), Cech & Myrick (1999), McCullough (1999), Sullivan et al. (2000), Myrick & Cech (2001), McCullough et al. (2001) and Hicks (2001). The following discussions are a summary of the findings of some of these reviews and of some individual studies.

4.2.7.1 Effects on reproductive capacity

If gravid adult salmonids are exposed to high water temperatures prior to spawning, their reproductive success can be affected. High water temperatures affect the vitality of their gametes (McCullough et al. 2001). Several studies have demonstrated this adverse effect.

In a review of the effects of elevated water temperature on the reproductive performance of adult chinook salmon, Marine (1992) reported that 15 - 17 EC led to sub-lethal effects in brood stock and caused increased infertility and embryonic developmental abnormalities. Berman (1990) observed that reproductively mature spring chinook salmon from the Yakima River held at 17.5 - 19 EC produced a greater number of pre-hatch mortalities and developmental abnormalities, as well as smaller eggs and alevins than adults held at 14 - 15.5 EC. In the American River in California, Hinze et al. (1956), noted that egg eye-up rates exceeding 55% did not occur when eggs were taken from fall chinook salmon exposed to river water exceeding 15.5 EC. Similarly, Bouck et al. (1975) observed reduced reproductive capacity in adult sockeye salmon held at 16.5 EC as compared to 10 EC.

In adult coho returns from Lake Erie, Flett et al. (1996) partially attributed a decline in the quality of ovulated eggs to exposure of adults to surface water temperatures exceeding 20 EC.

4.2.7.2 Physiological and behavioral effects

Fish respond physiologically (altered growth and health) and behaviorally (movement, site selection, and interactions) to environmental conditions they encounter. Chronic stress caused by elevated temperatures directly affects these physiological and behavioral parameters and weakens the resistance of salmonids to other stressors (Thomas et al. 1986). Other than growth, the biological significance of the physiological changes caused by exposures to high water temperatures are not fully understood. Measurements of plasma cortisol and glucose or liver glycogens are commonly measured stress indicators in fish. If these measurements are to have application beyond research, they must be relatively uniform over a wide range of conditions. For example, the possible differences caused by additional stress and non-stress factors such as age, size, and nutritional status of the fish must be considered (Barton & Schreck 1987).

For this assessment, we used an alternative approach for identifying water temperatures causing adverse physiological and behavioral conditions. By definition, the most favorable physiological conditions for fish occur within the optimum temperature range for that species. The upper limit of the optimum range is 14 EC for chinook salmon (Brett 1952), 15 EC for sockeye salmon (Brett 1967), 14 EC for coho salmon (Brett 1952), and 14 - 15 EC for steelhead trout (Hicks 2001). Water temperatures exceeding the upper limits of these optimum ranges can be expected to cause physiological and behavioral responses as the fish adjust to their warmer environment. On a small scale, these adjustments may be measured by increased levels of glucose or cortisol in blood plasma or the depression of liver glycogens. On a larger scale, particularly in combination with other stresses, the health and survivability of the fish can be affected. For example, Barton & Schreck (1987) observed 40% mortality in juvenile fall chinook salmon exposed to crowding stress and 21 EC and no mortality in fish held at 7.5 EC with the same crowding stress.

4.2.7.3 Lethal effects

The lethal effects of high water temperatures for each salmonid species are summarized in Tables 4.1 to 4.5. They are not reviewed in detail here as these temperatures are well beyond what would be considered adequate for protecting the important fish species in the Columbia River basin.

4.2.8 Effects of increased temperature on adult bull trout

Bull trout occur across a major portion of their potential range in the Columbia River basin and are more commonly found in cold, high-elevation, low to mid order watersheds with low road densities (Ratliff & Howell 1992, Rieman et al. 1997). Due to habitat degradation and fragmentation, blockage of migratory corridors, poor water quality, past fisheries management practices, and the introduction of non-native species, the bull trout was listed in 1998 as threatened under the ESA (Lohr et al. 2001). Laboratory survival experiments by Selong et al. (2001) corroborate field observations suggesting that bull trout have among the lowest upper thermal limits of the North American salmonids.

Adult bull trout are known to move downstream in watersheds to overwinter in mainstem or reservoir areas (McPhail & Murray 1979, Fraley & Shepard 1989, Schill et al. 1994). Distances traveled between the tributaries and downstream overwintering areas commonly exceed 100 km (Schill et al. 1994, Swanberg 1996), and movements up to 275 km have been recorded (Burrows et al. 2001). Adult bull trout are believed to occasionally use nearly all mainstem and reservoir areas in the study area (Mongillo 1993). Life cycle requirements of concern for adult bull trout found in these areas are the effects of increased water temperature on growth, movement and distribution.

Field and laboratory growth studies for adult bull trout in relation to water temperature are not available. In a laboratory study with age-0 bull trout fed to excess, Selong et al. (2001) estimated by regression analysis that peak growth occurred at 13.2 EC. Above this level, the growth rate decreased sharply, falling to 60% and 19% of the peak growth rate at 18 EC and 20 EC, respectively (ibid.). Without qualification, it would be inappropriate to directly relate this laboratory growth study on juveniles to field conditions for adults. Nonetheless, it is indicative of the low temperature requirements needed for the growth of this species.

As with other salmonids, water temperature affects bull trout movements. Adult bull trout migrations usually occur at 10 - 12 EC (Buchanan & Gregory 1997) and water temperatures of 16 - 18 EC are believed to cause thermal blocks (Shepard 1985, M. Faler, personal communication cited in Thiesfeld et al. 1996). Their movements into tributaries appear to occur with both increasing and decreasing temperature cycles. With increasing water temperatures, adult bull trout moved from Upper Arrow Lake reservoir into MacKenzie Creek in British Columbia (McPhail & Murray 1979); from the Salmon River into Rapid River in Idaho (Elle 1995); and from the Blackfoot River into its tributaries in Montana (Swanberg 1996). Conversely, adults moved with decreasing water temperatures from the Flathead Lake to the North and Middle Forks of the Flathead River in northern Montana and southern British Columbia (Fraley & Shepard 1989); and from Lake Cushman to the North Fork of the Skokomish River on the Olympic Peninsula (Brenkman et al. 2001). Except for the study on the Blackfoot River, the threshold temperature for when fish moved was 10 - 12 EC. Fish began to move in the Blackfoot River at temperatures ranging from 12 - 20 EC (mean 17.7 EC). All of the above movements were spawning migrations and all, except for the one on the Olympic Peninsula, were in the Columbia River basin, and the movements occurred from approximately March through November.

The upper limit of the optimum range for the bull trout appears to be at or near 12 EC. Oregon Department of Environmental Quality (1995) identified a preference range of 9 - 13 EC for adult bull trout. Shepard et al. (1984) and Haas (2001) respectively found bull trout in the greatest densities and in the best condition at temperatures #12 EC. When water temperatures increase to levels exceeding their optimum range for bull trout, their distribution is reduced. Under these conditions, bull trout will move from the free-flowing main channel reaches or reservoirs within the study area to their natal streams or into thermal refugia.

4.3 Non-Salmonids

In the Columbia River basin, white sturgeon are present throughout the area of concern for this problem assessment. Their population numbers are stable in Lower Columbia River and in some of the reservoirs with contiguous upstream free-flowing reaches. However, in other reservoirs lacking critical spawning or rearing habitat their population numbers may be depressed (Coon 1978, Lepla 1994, North et al. 1993, Parsley et al. 1993, Devore et al. 1995, Beamesderfer et al. 1995).

Other cold-water fish species inhabit the area of concern for the problem assessment but their critical life stages are either not well defined, or they occur mainly in the tributaries to the main channel areas that are the subject of this problem assessment.

4.3.1 Effect of increased temperature on white sturgeon reproduction

White sturgeon spawn in main channel areas with high current velocity from April through July (Parley et al. 1993, McCabe & Tracy 1994). A high discharge rate (flow) appears to stimulate spawning activity. Water temperature is not an acute spawning cue as are high river discharge and water column velocity (Andres & Beckman 1995).

The amount of spawning habitat for white sturgeon is defined by the discharge rate and water temperature in the river. As the rate increases, areas with high water velocity increase, and the spawning period is further defined by the temperature range within which successful spawning occurs (Parsley & Beckman 1994). This fish spawns in water temperatures ranging from 10 - 18 EC, with most spawning occurring at 14 EC (Parsley et al. 1993). Successful egg incubation is possible with a temperature range of 10 - 18 EC, but best results occur at 14 - 16 EC. Temperatures 18 - 20 EC may cause substantial mortalities during sensitive embryonic stages, and temperatures above 20 EC are clearly lethal of white sturgeon embryos. Fungal infection of the developing eggs is also a concern with increased water temperatures. The embryonic stage of the white sturgeon is about 3 weeks long at 17 EC (Wang et al. 1985).

Upon completion of their embryonic stage, white sturgeon appear to be able to successfully withstand water temperatures higher than 18 - 20 EC. Cech et al. (1984) noted that growth of post-embryonic white sturgeon increased significantly from 15 - 20 EC, but there was no significant different from 20 to 25 EC.

4.4 Summary of the effects of increased water temperature on native fish

Two levels of concern for the effects of increased water temperature on chinook, sockeye, and coho salmon, steelhead and bull trout, and white sturgeon are provided in Table 4.6. They are levels of "Initial" and "Serious" concern. The level of initial concern is lowest level that may cause the adverse effect and, where needed, the agent causing the effect is also present (e.g., disease or a predator). The level of serious concern is when a fish population is exposed to conditions that will very likely cause the adverse effects listed in Table 4.6.

The temperature levels listed are intended to be for the above listed fish species as they occur in the Columbia River basin. In some cases fish, e.g., chinook salmon and steelhead trout, occurring in the southern part of their range in North America can withstand water temperatures higher than those discussed in the effects sections (Cech & Myrick 1999, Myrick & Cech 2001). Further, where information is not available or the information available does not allow for the listing of a temperature, a dash (i.e., "-") is provided. Also, note that the temperature requirements for bull trout are listed separately from those of the other salmonids.

From an overall review of the levels of initial concern, with some exceptions, it appears that most of the adverse effects will begin to occur as water temperatures increase to 13 - 15 EC. The exceptions at lower temperatures are the requirements for steelhead smoltification (<12 EC) and for low temperature levels (<12 EC) required by adult bull trout. The exceptions at higher temperatures (16 - 18 EC) are reduced salmonid growth, reduced chinook distribution, increased predation, and impaired bull trout holding and migration.

In a similar review of the levels of serious concern, there is some overlap because of the low temperatures required for smoltification of chinook, sockeye, and steelhead. The remainder of the temperatures fall in the 18 - 22 EC range. It should also be noted that as water temperatures increase into the 20+ EC range chronic and acute toxicity become a concern, particularly if the fish are sustaining multiple stressors, like passing through dams.

Except for bull trout, the time periods of concern for resident and migratory salmonids are shown in Figure 4-1. The time period of concern for bull trout would vary with location in the Columbia and Snake rivers within the study area, but would generally be during the late summer and early fall when adult fish are moving out of main channel areas into tributaries.

The time period of concern for fall chinook salmon spawning is from mid-October to the third week of November in the Columbia River and from mid-October to mid-December in the Snake River (Dauble & Watson 1997, Tiffan et al. 1999, Groves & Chandler 1999). Growth is an issue all year for yearling salmonids, and for subyearlings it is an issue from early March to mid-late September. The time periods of concern for outmigrating juvenile salmonids extend from early April to mid-late September, depending of the species. Returning adult salmonids are likely in the river all year long, but begin arriving in numbers at Bonneville Dam in early March and continue up the Columbia River until about mid-November and up the Snake River until early-mid December.

The period of concern for white sturgeon spawning and incubation is from April through August each year. Depending on the location in the river, white sturgeon may spawn from the end of April through July (Parsley et al. 1993, McCabe & Tracy 1994). The spawning period is followed by a 3-week incubation period (Wang et al. 1985).

Excluding fish species usually found in the estuary, there are about 20 families of fish that occur in the study area, of which 10 are native (Wydoski & Whitney 1979). This assessment covers the temperature requirements for two of these families, which includes all fish species listed under the Endangered Species Act and nearly all fish of commercial and recreational importance.

Table 4.6: Summary of the effects of increased water temperature on the important fish species of the Columbia River basin.

Effect/Concern - Salmonids	Water Temperature (EC)	
	Initial Concern	**Serious Concern**
Increased mortality to eggs incubating in the gravel[1]	14	-
Abnormal egg/larval development resulting from the exposure of adults to high temperatures[1]	15	17
Impaired juvenile pre-smolt physiology, excluding growth - Chinook salmon - Sockeye salmon - Coho salmon - Steelhead trout	 >14 >15 >14 >14	 - - - -
Impaired adult bull trout physiology	>12	-
Impaired smoltification, slows or halts outmigration - Chinook salmon - Sockeye salmon - Coho salmon - Steelhead trout - Bull trout	 13 13 14 12 -	 15 15 17 14 -
Reduced growth by juveniles[1] Reduced growth by subadult and adult bull trout	18 16	21 18
Reduced juvenile distribution - Chinook salmon - Sockeye salmon - Coho salmon - Steelhead trout Reduced distribution of subadult and adult bull trout	 17 - 18 - 15 - 13 - 14	 20 - 22 - 18 20 - 22 16 - 18
Increased predation on juveniles[1]	16	21
Increased disease	15 - 16	18 - 20
Adult migration stopped[1] Adult bull trout migration and holding impaired	- 16	21 -

Effect/Concern - Non-Salmonids	Initial Concern	Serious Concern
White sturgeon fail to reproduce or have an unsuccessful 3 - week incubation	>17	>18

Notes: 1. Does not include bull trout.

Figure 4-1: Time periods of concern for subyearling, yearling, and adult salmonids moving through or residing in the study area.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	References
Spawning													Dauble & Watson 1997
Juvenile Migrations													Fish Passage Center &
Growth													Fish Passage Center &
Adult Migrations													Dauble & Mueller 1993
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	

Notes: RIS = Rock Island Dam, LGR = Lower Granite Dam, BON = Bonneville Dam, JDA = John Day Dam, WEL = Wells Dam

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